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**Energy Systems Optimisation for Net Zero
Community: Modelling and Simulation**

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Abstract

The Paris Agreement and the commitments of countries to contain global warming and reach climate neutrality, entails a movement towards Net Zero. While there are numerous definitions of Net Zero in scientific literature, in the scope of this work, the Net Zero Community (NZC) was defined as a community that produces locally as much renewable energy as it consumes, thereby achieving a balance of net zero energy consumption. This dissertation presents desk research, modelling, simulation, and analysis of various microgrid configurations with the aim to identify an optimal, in terms of efficiency and costs, NZC energy system for the community of Palecastro, in Crete, Greece. It focuses on electricity generation and the residential sector. The research supports that determining the optimal energy system for a specific NZC, is a complex process and depends on a variety of factors, including geographic location, energy demand, resilience and reliability of the microgrid, and the economic viability of investment. Localised Distributed Energy System, involving rooftop PVs and batteries in each house, and a community wind turbine, is the optimal microgrid configuration, in terms of self-sufficiency, while it goes beyond Net-Zero towards a Positive Energy Community. Nevertheless, the most economically profitable solution is the microgrid that combines a PV park and high-power community wind turbine, without energy storage. Overall, the "Cost of No-Action" is always higher than any net zero scenario. This work provides elements for consideration for energy engineers, community leaders and planners, as they plan the net zero transition of their communities. In addition, it identifies areas for further research in the field of energy modelling.

Keywords: Net Zero Community, Microgrids, Positive Energy Community, Energy Modelling, Decarbonisation of buildings, Decentralised Renewable Energy Systems, Energy Storage, Climate Mitigation measures, Climate Action Targets.

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Glossary

Definitions

Net Zero	Net zero refers to a state in which the greenhouse gases going into the atmosphere are balanced by removal out of the atmosphere. [1]
Net Zero Emission	Balances the whole amount of greenhouse gas (GHG) released and the amount removed from the atmosphere. [2]
Net Zero Carbon Emission	Means that an activity releases net-zero carbon emissions into the atmosphere.[2]
Carbon Neutrality	Carbon neutrality means having a balance between emitting carbon and absorbing carbon from the atmosphere in carbon sinks. [3]

Polysun Indicators

Yield Photovoltaics AC	Energy production of the photovoltaic inverters (AC)
Self-consumption	Own electricity production which is used to meet the demand and to charge batteries.
Total electricity consumption of the system	Balance of electricity consumed from the grid and fed into external grid
Total electricity consumption	Sum of the self-consumption and the electricity consumed from the external grid.
Energy deficit	Difference between the demanded energy and that effectively consumed.
Battery discharging energy	Energy obtained from discharging the battery.
Total energy consumption	Energy effectively consumed by the consumers, including the energy consumption for domestic hot water, for heating and cooling of the building.
Solar fraction	Percentage of energy to the system supplied by the sun.
Solar thermal energy to the system	Energy transferred by the collectors to the water.
Heat generator energy to the system	Energy transferred by the electrical and fuel-powered heat generator to the water.

List Of Abbreviations

<i>Acronyms</i>		<i>Technologies</i>	
EU	European Union	PV	Photovoltaic
NZC	Net Zero Community	HP	Heat Pump
NZE	Net Zero Emission	ST	Solar thermal
RE	Renewable Energy	HVAC	heating ventilation air conditioning
RES	Renewable Energy Sources	<i>Units</i>	
RET	Renewable Energy Technologies	<i>kWh</i>	Kilowatts hours
GHG	Greenhouse Gas	<i>ktoe</i>	Thousands tonnes of oil equivalent
O&M	Operational and Maintenance	<i>W</i>	Watts
NECP	National Energy and Climate Plan	<i>GJ</i>	Gigajoule
EWE	Export Wind Electricity [Wh]	<i>MWh</i>	Megawatt hours
		<i>mph</i>	Mile per hour
		<i>Currencies</i>	
		€	Euro
		£	Pounds
		\$	Dollar

1 Introduction

The Paris Agreement and the subsequent European Green Deal set ambitious targets to reach climate neutrality by 2050. This involves policies and measures to limit global warming to 1.5°C or below, compared to pre-industrial levels. This requires drastic cut of greenhouse gas emissions, resulting to a "Net Zero" movement.

Renewable energy technologies have been improving drastically in terms of efficiency and cost reduction over the last years. Yet, nearly 80% of the world's primary energy is provided via fossil fuels such as oil, coal, and natural gas [4]. The resulting high greenhouse gas emissions, rising energy costs and the uncertain geopolitical situation, driven by the Russian invasion of Ukraine, urge countries around the globe to take action to decarbonise their economies, by diversifying energy sources and stepping up net zero carbon solutions.[5]

1.1 Aim, Objectives and Scope

The aim of this dissertation is to study the optimisation of a Net Zero Community (NZC) energy system, by modelling, simulating, analysing and comparing, in terms of energy performance and cost-efficiency, diverse microgrid configurations that are capable of transforming a small traditional community in Crete, Palekastro, to a Net Zero Community.

Its objectives are to:

- design and develop a framework for evaluation of different microgrid configurations to achieve a NZC in the community of Palekastro, Crete
- select suitable energy modelling tools and software for the analysis of results

- design suitable scenarios for the simulations, collect and analyse data
- determine optimal solutions following a multidimensional approach, including the system's performance, reliability, self-sufficiency and economic viability
- identify research challenges in the future.

The research is based on energy modelling and simulation of different energy systems, involving microgrids, i.e. decentralised renewable energy resources (DERs) and technologies for electricity generation and storage, as well as on analysis of their performance, efficiency, and economic viability of investment.

The scope useful to this work, covers the decarbonisation of the two most important energy sectors of the community, namely electricity generation, and the residential sector. Other sectors, such as transport, industry and agriculture, are also important for the net zero transition, but are not considered in this project, due to the high complexity and the lack of suitable modelling tools. With regards to energy efficiency policy and measures, these are top priority for achieving net zero targets in all energy sectors. However, simulating such measures requires a very a sophisticated process and could not fit in the scope of this dissertation. Yet, some simple energy efficiency measures were factored in, for example limiting the use of batteries solely during the demand peak hours.

The findings can serve to inform and guide energy designers, engineers, community leaders and civil organisations, while they pursue their communities' net zero energy targets.

1.2 Geopolitical Context

Desk research about Palekastros energy consumption profile, derived the following information, useful for the community's energy modelling:

1.2.1 Palekastros, Greece - outlook

- Location: Eastern part of Crete, Greece.
- Population: 1000 inhabitants
- 300 single-family houses: approximate estimation through Google Maps.
- Long hours of sunlight during winter and summer. [6]
- Mediterranean Climate. The average temperature is showing in Figure 1.1a.
- Strong wind conditions (Fig. 1.1b)

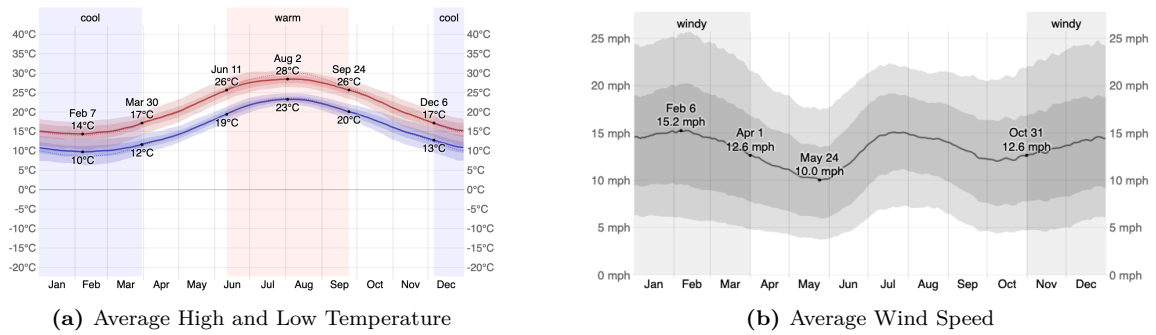


Figure 1.1: Weather Conditions in Palekastros, source: [6]

1.2.2 The Greek energy sector: an overview

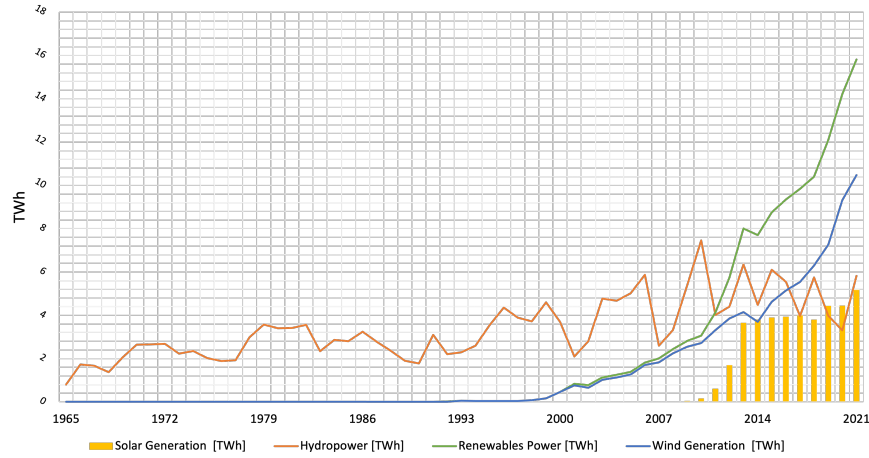
The Greek energy sector depends heavily on fossil fuels. Oil and natural gas together accounted for 73% of primary energy consumption in 2021, (Table 1.1). Natural gas is used as the main transition fuel to pave the way towards the green transition. Lignite is the main national fossil fuel, which, in 2018, still accounted for 29% of electricity generation in Greece. [7]. The Greek islands are a major issue of concern, in particular those that are not interconnected with the mainland. While renewable energy sources are ample, electricity in these islands is generated mostly from highly polluting diesel generators.

Nevertheless, there is significant progress made in renewable electricity generation since 2000, as shown in Figure 1.2, driven by solar, wind and hydropower. Greece has started

Table 1.1: Primary energy consumption by fuels of Greece in 2019 and 2021, *Data Source:*[8], [9]

Years	Units	Oil	Natural Gas	Coal	Nuclear energy	Hydro electric	RE	Total
2019	TWh	180.56	52.78	61.11	-	11.11	33.33	330.56
	%	54.62%	15.97%	18.49%	-	3.36%	10.08%	100%
2021	TWh	143.19	69.80	20.55	-	15.24	43.75	292.54
	%	48.95%	23.86%	7.03%	-	5.21%	14.95%	100%

to tackle the problem of global warming and has been decreasing its primary energy consumption rapidly since 2007. Yet, to reach its target to become carbon neutral by 2050, Greece will need to maximise its electricity production from renewable sources.


Figure 1.2: Graphs on RET power of Greece from 1965 to 2021, *Data Source:*[8]

1.2.3 Policy Context in Greece: Climate Targets and Policies

The United Nations Intergovernmental Panel on Climate Change (IPCC) report [10] underscores that global greenhouse gas emissions are still rising (Figure 1.3), and that they have to start decreasing by 2025 at the latest. Cities and communities are important part of this net zero transition and they need to take urgent measures to improve energy efficiency; deploy near net-zero energy systems; decarbonise the building stock; promote electric vehicles for public transport and shared mobility; and implement a local circular economy.

The European Union, has adopted the European Green Deal and the European Climate

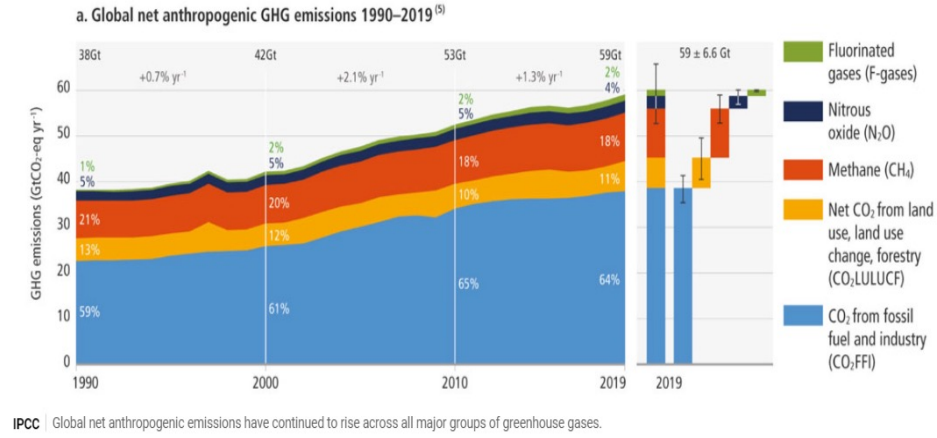


Figure 1.3: A Global net anthropogenic GHG emissions from 1990 to 2019 [10]

Law with the target to achieve climate neutrality by 2050 and limit global warming to below 1.5°C. In the medium term, the EU agreed the “Fit For 55” legislation [11], outlining measures to cut emissions by at least 55% by 2030.

In this political context, Greece developed its National Energy and Climate Plan (NECP) [7], committing by 2030, to:

- Reduce greenhouse gas emissions by 55% in comparison to 1990.
- Decrease final energy consumption by 38%;
- Increase the share of RES to 35% of final energy consumption, as follows: 61% of final electricity consumption; 42.5% of final energy for heating and cooling; and 19% of final energy for transport.
- Increase inter-connectivity with neighbouring countries to 21%.

2 Literature research

In scientific literature there are numerous definitions of NZC, a fact that complicates the design and monitoring of NZC. Haleh Moghaddasi et al. [12] argues that the diverse definitions of a net zero community pose a challenge for stakeholders, including engineers, researchers and policymakers, who are striving to implement and monitor the progress of NZC. According to Polly et al. [12], stakeholders encounter difficulties due to a lack of documented processes, tools, and established best practices that could aid them in achieving net zero energy transition.

Research related to the design, implementation, and operation of net zero energy systems underscore the need for a multidimensional approach, focusing on:

- **Decarbonisation of electricity** can be implemented through **microgrids**, i.e. small-scale, localised electricity systems that can operate either autonomously, as an islanded microgrid, or connected to the main grid. Chartier et al. [13] presents a general outlook of microgrids, which consist of distributed renewable energy resources (DERs) such as solar photovoltaic (PV) panels, wind turbines, and energy storage systems. The analysis finds that microgrids foster the resilience of the grid and improve its response, by timely offsetting excess or deficit in energy supply at local level. Microgrids enable and accelerate the deployment of renewables. In addition, because they use local energy sources to serve local demand, they decrease energy losses during transmission and distribution, and increase the efficiency of the grid.

One of the critical aspects of microgrid design is control strategies that ensure reliable and stable operation. Wang et al. [14] studied the reliability assessment of microgrids with different control strategies, including master-slave (centralised), peer-to-peer (decentralised) and hierarchical control. Javadi et al. [15] proposes a

hierarchical control strategy that allows for effective operation of a microgrid with different types of DERs. The proposed control strategy uses a central controller to manage the overall operation of the microgrid and distributed controllers to manage the DERs' individual operations.

Optimisation of microgrid design is critical. Kamal et al. [16] and Farzin et al. [17] explored microgrid planning and optimisation to determine the optimal configuration of DERs and energy storage systems. They propose a multi-objective optimisation approach, which considers different objectives such as cost, efficiency, reliability, and environmental impact, and uses efficient algorithms to determine the optimal design.

- **Decarbonisation of buildings**, which account for over 40% of greenhouse gas emissions [18]. The combined residential, commercial and public services sector accounted for 40% of total final energy consumption in Greece, in 2020 (Table 2.1). Amini Toosi et al. [19] and Camarasa et al. [20] determine the key elements for decarbonization of buildings, being: improving energy efficiency, through retrofitting and energy-efficient appliances; integration of RES, i.e. solar panels, wind turbines, or geothermal systems to power the energy needs for heating, cooling, and electricity; transitioning to electric heat pumps and electric appliances; using low-carbon, recycled materials and sustainable construction practices; cost-effective and efficient energy storage technologies, such as batteries, thermal energy storage, hydro-pump and hydrogen storage, that enable the management of energy supply and demand and ensure the stability of the microgrid; using advanced Building energy management systems (BEMS) that incorporate artificial intelligence (AI) and machine learning to optimise energy usage and improve building performance; and adopting sustainable building practices by complying with **green building certifications and standards**, such as LEED (Leadership in Energy and Environmental Design) or BREEAM (Building Research Establishment Environmental Assessment Method).
- **Electrification of transport**

Table 2.1: Total Final Consumption by sector in Greece, 2020, *source:*[21]

Transport	215279	TJ	35%
Residential	176139	TJ	29%
Industrial	105655	TJ	17%
Commercial & public services	66996	TJ	11%
Waste energy	34364	TJ	6%
Agriculture	11610	TJ	2%
Total	610043	TJ	

The electrification of transport (electric cars, bicycles, public buses, trains, or shared electric mobility services) is crucial, as the transport sector accounted for 35% of total final energy consumption in Greece, in 2020 (Table 2.1).

Haleh Moghaddasi et al.[12] highlights that electrification of transport is only beneficial if the electricity is generated by RES, thus accelerating the integration of Decentralised Renewable Energy, by integrating EVs charging infrastructure with local renewable energy generation. It enhances Smart Charging and Demand Management, by encouraging EV charging during off-peak hours when renewable energy generation is high. In addition, it promotes Vehicle-to-Grid (V2G) technology, that acts as distributed energy storage system connected to the grid, hence supporting grid stability, load balancing, and optimal utilisation of RES.

- **Decarbonisation of agriculture**

Agriculture contributes an important amount of green house gas emissions, hence decarbonisation of agriculture plays a key role, especially for rural communities. Soofi et al. [22] presents a roadmap consisting of the following elements: sustainable farming practices that promote soil health and reduce the use of synthetic fertilisers, thus leading to lower emissions; integration of Renewables (agrivoltaics, wind turbines, and bioenergy systems) to power farming processes; integrating trees, as carbon sinks, and to enhance soil fertility, and biodiversity; improved livestock management, and methane capture systems to reduce Methane and Nitrous Oxide; efficient water management practices, such as precision irrigation systems and water conservation techniques; implementing circularity in agriculture, such as recycling organic waste and using it as compost or bioenergy

feedstock, to reduce emissions and enhance nutrient cycling.

- **Net Zero Industry**

The role of industry, which accounted for 17% of final energy consumption in Greece in 2020, is capital in succeeding the transition towards a net zero economy. According to Svensson et al. [23] the industry sector is also the harder to decarbonise, because of the energy-intensive industrial processes. It requires: improving energy efficiency in industrial processes, through energy management systems; shifting to renewable energy systems, such as solar panels or wind turbines, or procuring renewable energy through power purchase agreements; deploying Carbon Capture and Storage (CCS) technologies, particularly in energy-intensive industries like cement, steel, and chemicals; implementing circular economy by recycling and reusing materials and designing closed-loop systems.

- Overall, **well-designed government policies and incentives** can effectively promote the implementation of NZC and create a positive environment for investments. These may include financial incentives, tax credits, regulations, and building codes that encourage energy-efficient processes and products and renewable energy adoption. Likewise, it is crucial for **citizens to change behaviour** and adopt sustainable, energy-efficient practices in everyday life.

The Cost of the Net Zero Transition worldwide

Estimating the exact cost of the global net zero transition is complex, due to continuous technology developments, a multiplicity of policy responses, and rapidly changing energy markets. However, several studies and reports have provided estimations about the potential cost of the transition:

- According to the International Renewable Energy Agency (IRENA) [24] the full transition to renewable energy by 2050 is technologically achievable, but it requires significant investments, policy changes, and global cooperation. This involves

increasing the global renewable energy capacity six-fold and investing around \$131 trillion in renewable energy and energy efficiency measures by 2050.

- A recent study by Stanford University researchers [25] concludes that it is technically and logistically feasible for countries to meet 80% of their energy needs from wind, hydroelectricity, and solar power by 2030, with a complete transition to 100% renewable energy by 2050. It argues that while the net zero transition of the global economy would require an upfront cost of \$73 trillion globally, its payback period would be only seven years and in addition it would create 28.6 million additional full-time jobs. The study includes comprehensive roadmaps for 143 countries - responsible for 99.7% of emissions - to successfully achieve a complete transition to renewable energy by 2050.
- The International Energy Agency (IEA) [26] report in 2021, estimates that an additional annual investment of around \$1 trillion is needed to achieve net zero emissions by 2050 and presents a global roadmap. This requires all governments and policymakers to implement their energy and climate policies, which follow different pathways to achieve their climate neutrality goals by 2050. Despite the good progress made, current pledges by different countries are insufficient and would still leave 22 billion tonnes of CO₂ emissions. Therefore much higher commitment is needed, by countries, cities and communities alike.
- The Global Commission on the Economy and Climate estimated in its New Climate Economy report that the transition to a low-carbon economy would require additional investment of approximately \$1 trillion per year globally from 2015 to 2050. This investment would support efforts to reduce emissions and promote sustainable economic growth.

These costs may seem enormous, however, it is important to factor in the considerable **long-term environmental and social benefits** of the net zero transition, such as reduced emissions and energy prices, energy security, improved public health, and job creation in the renewable energy sector, make the transition to renewable energy eco-

nomically justifiable. Additionally, as technology continues to advance and costs are falling, the overall cost of the global net zero transition is expected to decrease drastically. It is important to estimate the **Cost of No-Action**, for instance the economic impact of extreme weather conditions and poor health, could far exceed the costs of the net zero future.

In this context many countries, cities, communities and businesses alike are setting ambitious targets for renewable energy integration and are actively working to implement them.

Therefore the **research question** is to define a framework for evaluation of a NZC, in terms of energy efficiency and costs; explore the optimisation of a NZC system; and determine the optimal microgrid configuration of distributed renewable energy resources and technologies, that serve fully the local community load, and hence contribute to achieving the global Paris Agreement targets.

3 Methodology: energy modelling and simulation scenarios

This chapter describes the methodology and tools used for the simulations. First, we start by identifying the community’s energy needs. Secondly, we outline three scenarios of microgrids, capable of powering a Net Zero Community. Thirdly, we elaborate on the energy modelling tools used to analyse these scenarios, including relevant hypotheses and assumptions. Finally we describe the methodology for the economic assessment of the investment, with a view to identify the optimal energy system in terms of performance and cost-efficiency.

3.1 Energy demand of the community

The final energy consumption in Greece in the residential sector is shown in table 3.1.

Table 3.1: Final consumption for household sector [ktoe], *Source: Eurostat*[27]

	2018	2019	2020	2021
EU - 27 countries	249,747	248,189	248,128	261,813
Greece	3,914	4,114	4,290	4,279
	1.57%	1.66%	1.73%	1.63%

To calculate the energy consumption per capita in kWh, the value is converted from ktoe to kWh (1 ktoe = 11,630,000 kWh) and then divided by the population of Greece (10.64 million). To estimate the energy needs of Palecastro, we multiplied the per capita energy consumption by the population of Palekastros (1000 persons):

Greece’s final consumption per capita, in kWh:

$$4,278 \cdot 11,630,000 \text{ kWh} = 49,753,140 \text{ MWh}$$

$$\frac{49,753,140,000}{10,640,000} = 4676.05 \text{ kWh/capita}$$

The energy demand of Palekastros for the residential sector is roughly estimated to:

$$4,676.05 \text{ kWh/capita} \cdot 1000 \text{ population} = 4,676 \text{ MWh}$$

We observe that the final consumption for the residential sector in Greece is very low compared to other European countries. This can be attributed mostly to the mild weather conditions and the extended use of solar thermal collectors in Greece.

3.2 Scenarios outline

Recognising that solar and wind power are the main renewable energy sources in a southern European community like Palekastros, the following working hypotheses are made:

- The Community will seek to maximise its energy self-sufficiency, by using PV and wind turbines for its local electricity production.
- Li-ion batteries are used for energy storage.
- Solar thermal collectors are used for hot water.
- Heat pumps will serve only as a backup source, in case of insufficient RES.
- The role of electrification of transport, industry, agriculture, in enabling a NZC is not explored in this project.

Based on these hypotheses, three different scenarios for energy systems, shown in Table 3.2, were modelled, tested and analysed to identify the best-performing solution. An outline of these scenarios is described below, while a more thorough description of their configuration is provided in section 3.4

Table 3.2: Scenarios to be simulated

Technologies	Scenarios		
	1	2	3
PV Park	✓		✓
PV on rooftops		✓	
Solar thermal on rooftops	✓	✓	✓
Wind Park	✓	✓	✓
Domestic battery storage		✓	
Utility battery storage	✓		

Scenario 1: A combination of a community PV park and wind park with battery storage will supply electricity to the community. In addition solar thermal collectors installed on houses rooftops will cover the needs in hot water. The choice of PV parks has the advantage of easy and fast installation, as well as creating economies of scale by using less components (cables, inverters, support structure) than rooftop PVs.

Scenario 2: This scenario consists of rooftop PV and solar thermal panels with energy storage in each dwelling, as well as a wind park. It estimates the total energy capacity of decentralised energy systems where each dwelling becomes "prosumer" (producer and consumer). The advantages of rooftop panels are mainly saving land that may be used for agriculture, and lower maintenance costs compared to PV parks.

Scenario 3: It is based on a combination of community solar park and wind park, with solar thermal panels installed on each rooftop, but without any energy storage system. Therefore, although the solar park's capacity is identical as in scenario 1, the wind turbine will play a significant role in this scenario and is selected to be more powerful, to compensate for the fact that there is no energy storage.

3.3 Energy modelling tools

For the purpose of this project, the **energy modelling software Polysun** was used to simulate the three scenarios. All three scenarios involve PVs (either a community solar park or rooftop PVs), as well as a wind park to supply for the electricity needs of the community. Polysun functions well for simulating various PV and energy storage

models, however it does not allow for combined simulation of wind turbines. Therefore, I developed the following innovative solution for wind power simulation:

1. Wind power simulation

Given the importance of wind energy in our experiments, we used a combination of Polysun and data on hourly energy production from wind turbines using [Renewables.ninja](#), a platform developed by Imperial College London and TU Delft. Renewables.ninja uses the MERRA-2 (global) database created by NASA for "global reanalysis to assimilate space-based observations of aerosols and represent their interactions with other physical processes in the climate system." [28].

Python coding

A tailor-made Python program was developed that assembles, aligns and analyses the results obtained from Polysun (PV modules and batteries) and from Renewables.ninja (for wind turbines). This analysis enabled the calculation and plot of the hourly electricity consumption and production in 2019, from a combination of renewable sources, namely solar, wind, battery, and import from the external grid.

The assumption was made that the community energy demands are covered in the following order: first by direct solar energy consumption, secondly from energy storage discharge, and thirdly by direct wind power generation. To be noted that it was not possible to simulate in Polysun the battery charge from wind energy.

By leveraging the hourly data, the Python program plotted accurately the hours of direct consumption of wind energy, as well as the amount of energy consumed, for every day of the year. Furthermore, by considering the overall demand of the community, the direct-consumption of wind energy, and the total energy generated by the wind turbine, it was possible to precisely calculate the amount of electricity imported from / exported to the grid.

The various hourly data were organised in an excel file and processed by the Python program: the Community energy demand; the electricity production from

wind [in W]; the direct consumption from PV [in W]; the Battery discharge [in W], which was restricted to work during the demand peak hours. Based on the above data, the "Remaining demand after direct PV and battery consumption" was calculated by subtracting the combined direct consumption from PV and the battery discharge from the total hourly energy demand. This remaining demand should be covered by wind-generated electricity in order to minimise reliance on the external electricity grid.

$$\text{Remaining Demand after direct PV and battery consumption [W]} = \text{Demand [W]} - (\text{Direct consumption PV} + \text{battery discharging}) \text{ [W]}$$

At a second stage, the "Remaining energy (after direct wind consumption) to be exported to, or imported from the grid" was calculated by subtracting the Remaining Demand after direct PV and battery consumption from the wind electricity production (based on hourly data from Renewables.ninja). This step provided insight into whether the community had surplus energy that could be exported to the grid or additional energy needed to be imported from the grid to meet the demand.

$$\text{Remaining energy after direct wind consumption, to be exported to, or imported from the grid} = \text{Wind production} - \text{Remaining demand.}$$

Lastly, the hourly direct wind consumption was calculated. When the above "Remaining energy after direct wind consumption, to be exported to, or imported from the grid" was a positive value, this meant that the wind power was enough to cover the last part of community demand, and the remaining energy was fed into the external grid. On the contrary, when the above value was negative, this meant that the entire wind energy was directly consumed and that that additional electricity is needed from the grid. The sum of the positive values calculated the amount of electricity that was fed into the external grid. Likewise, the sum of the negative values determined the amount of electricity imported from the grid.

Functionality of the Python program The code is designed to function in the following steps: First, it is importing several libraries such as pandas, numpy, matplotlib, seaborn, and time data to process and visualise data. Second, reads excel file converted to CSV file into a pandas dataframe. A specific function was used to calculate the mean production for each month and date for the wind, solar and battery. A stacked bar plot was created for each month using the mean production data, displaying the mean production for four types of production: Wind, Solar, Battery, and Demand. The matplotlib library was used to create the stacked bar plots and creates subplots for each month using a 3x4 grid. It then loops through each subplot and selects the data for the corresponding month. The code also converted the month number to month name using the time library and adds labels and legends to the plot.

2. Assumptions

For the simulations in Polysun, the following assumptions were made:

- (a) The average daily hot water demand is around 40 litres per capita.
- (b) Each household consists of 3 people.
- (c) The PerMod battery system is set from 6 to 10 pm.
- (d) The Deep cycle threshold of the battery is set to 66 (Polysun recommendation). A deep-cycle battery is a battery meant to be used often and drained completely before recharging.
- (e) The hot water temperature is set to 50 °C.
- (f) Hot water is destined to residential use only (not for space heating) and is provided by solar thermal panels (see analysis below).
- (g) The absence period is set to never.
- (h) Initial state of charge of the battery is set to 0.
- (i) Solar Collector Model: UNIKO P21 from Pleion, flat plate collector. Specifications are provided in Table [A.1](#) in the appendix.

- (j) Photovoltaics panel model: LR4-72HBD-450M from Longi Solar. Specifications are in Table A.2 in the appendix.
- (k) Wind turbine models used and their specifications are in Table A.3, A.4 and A.5 in the appendix.
- (l) Battery units model: PerMod system from Polysun.
- (m) HVAC is used to heat the space.

3. Tilt angle optimisation for PVs

To identify the optimal tilt angle for the scope of this project, we simulated the function of ten PV modules, using different tilt angles, as shown in figure 3.1.

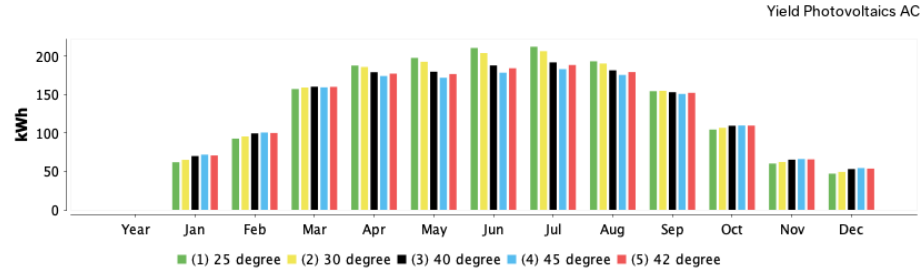


Figure 3.1: Tilt angle Optimisation

Table 3.3: Results of Yield PV in tilt angle optimisations

	Units	25°	30°	40°	45°	42°
Yield Photovoltaics AC	kWh	1,681.1	1,674	1,632.1	1,597.6	1,619.4

The results are shown in table 3.3. While the 30°angle is usually recommended, and the 25°angle accounts for the highest annual electricity production and is particularly higher than other angles during spring and summer, yet, during the winter period, a steeper PV tilt performs better.

The optimal tilt angle for Palecastro

Through simulations with different tilt angles, the optimal angle was sought, with a view to maximising self-consumption and minimising electricity imported from the grid, in the community of Palecastro. In this context, it was important to maximise PV yield during winter (when PV yield is in general lower and energy demand higher) therefore the **optimal tilt angle was found to be 42°**.

4. Assumption for solar collectors for hot water use

Due to the extended sunny weather, hot water in Crete can easily be obtained from solar thermal collectors or, less often, from heat pumps. For this project, the hot water use does not cover space heating because water heating requires 4184 J/kgK at 20°C and the air requires 1006.1 J/kgK at 20°C . That is four times more energy to heat the water, meaning that the electricity to heat the water from a heat pump is approximately 3 to 4 times higher than heating the air.

Therefore, the assumption is made that solar thermal panels are used to heat the water during the day, and it is stored in a tank of 50 L/resident.

3.4 Configuration of the three scenarios

3.4.1 Scenario 1

The first scenario (Figure 3.2) involves a solar park and a wind park that will supply clean electricity to the community, a utility battery storage to store the excess electricity and use it during the peak hours.

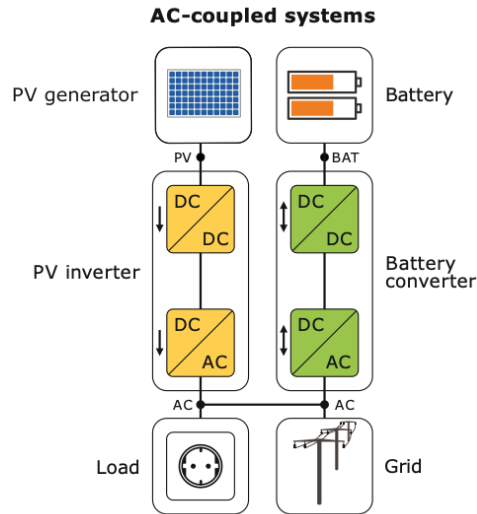


Figure 3.2: Energy system with PV and AC battery technologies

1. Electric Grid Profile

First, the grid is three-phase, meaning that the electrical current is divided into three separate waves that are out of phase with each other. This type of grid allows for a more efficient distribution of power compared to single-phase systems. The voltage in the grid is 230V/400V and the frequency is 50Hz. This means that the electrical current in the grid alternates at a rate of 50 cycles per second.

Second, the local voltage in the grid is 400V. This is the voltage level at which electricity is supplied to the end-users in the area. The voltage level is chosen to balance the need for energy efficiency and safety, as higher voltages result in lower electrical resistance and a higher risk of electrical shock.

Finally, the grid in this scenario does have a feed-in power limitation, meaning that any excess electricity generated by renewable energy sources after charging the batteries is fed back into the grid for others to use. This allows for more efficient use of renewable energy and helps reduce the demand for non-renewable sources.

2. Solar energy production

In the first scenario, a 2.47 MW PV park is installed, consisting of 5500 PV panels of 450W capacity each. They are oriented towards the south, with a tilt angle of 42°, to optimise the energy generation potential, as explained above. This results in an average yearly generation of 4168.1 MWh of solar electricity. The solar park choice has the advantage of faster implementation, and less infrastructure requirements.

3. Battery energy storage

With Polysun, the use of 350 lithium-ion batteries was simulated, using the program PerMod. The nominal capacity of each battery was 3.685 kWh, resulting to a total of 1.3 MWh at community level.

PerMod is an open source Performance Simulation Model designed to evaluate the energy efficiency of grid-connected PV-Battery systems used for residential

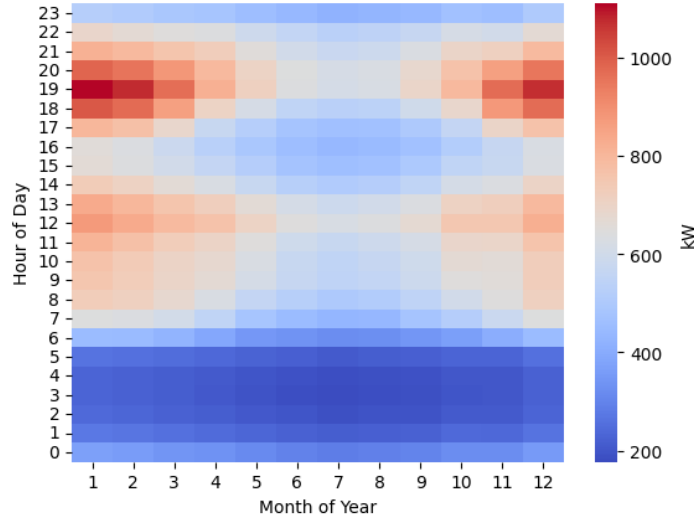


Figure 3.3: A heatmap demand of the day for each month

purposes. The model can simulate power flow for AC-, DC-, and PV-coupled systems with a time resolution of one second over a one-year period. This enables the assessment of overall system efficiency for the three topologies using the System Performance Index (SPI), which is crucial for comparing different products. Additionally, PerMod can be used for detailed loss analyses and assessments of various measures to optimise overall system efficiency.[29]

Polysun allowed for the charging of the energy storage system from the photovoltaic inverters only, but not from the wind turbine. Therefore, the simulation results are suboptimal.

4. Wind energy production

Two options were considered: either using multiple small low-power wind turbines in a wind parc, or using one high-power turbine. The small size of the community made more efficient the use of one only wind turbine. In order to identify the optimal wind turbine for each scenario, four different wind turbines of different brands, power and hub heights were simulated and the results are presented in the Results section.

3.4.2 Scenario 2

In the second scenario, the energy system consisted of rooftop PV modules and energy storage systems installed in each one of the houses in Palecastro. This configuration has the advantage of a distributed renewable energy system or microgrid, incurring cost savings in terms of land, infrastructure and maintenance. The assumption is that each roof is equipped with two type of panels: the photovoltaics to produce electricity and the solar collector to collect hot water from the sun.

1. Electric Grid Profile

This system involves a single-phase AC, 230V with 50Hz frequency grid connection, which is typically used to power residential and small commercial buildings in many countries worldwide.

2. Solar energy production

The simulation of the second scenario assumed 10 PV modules installed on each rooftop, at a tilt angle of 42°facing south to maximise their energy generation potential. This means that the total number of PV modules in the community is (10 x 300 houses) 3000, much less than the 5500 modules installed in scenario 1. Wind energy must compensate for this gap.

The type of PV panels used in this scenario is described in detail in table [A.2](#), with each panel having a capacity of 450W, resulting to 1.35 MW installed solar capacity at community level. Each house's total nominal power in DC is 4.5kW, which results in an average yearly generation of 7309.9 kWh of solar electricity per house.

To calculate the total energy imported from the grid for the community, the per household energy demand and direct consumption from PV, and battery discharge was multiplied by 300 (houses) and was analysed in conjunction with the wind production.

3. Wall battery unit in each house

According to the Permod simulations in Polysun [30], each house in the community will have one domestic battery. This means that the community will have a collective battery power of:

$$300 \times 3.685 = 1105.5kWh = 1.1MWh$$

The advantages of a distributed energy storage system are improved energy management and efficiency. With the PerMod program of Polysun, the community can benefit from a total of 1.1 MWh of energy storage capacity, which can be used for balancing the local energy supply and demand.

The domestic batteries from the PerMod program of Polysun are designed to be efficient and reliable. They can store energy during off-peak hours when the energy demand is low and release it during peak hours. This helps to reduce the overall energy consumption of the community and can lead to significant cost savings.

4. Wind energy production

Increased wind energy is needed to compensate for a decreased solar energy capacity in this scenario. Therefore, for this scenario four different wind turbines were simulated with higher power than in scenario 1.

3.4.3 Scenario 3

The third scenario involves a similar configuration as in the first scenario, but without any energy storage, and with wind turbines of higher power (from 1300 to 2000 MWh), to compensate for the lack of energy storage system. It is designed to explore the feasibility and reliability of a microgrid that is not equipped with energy storage, and how it impacts the investment assessment.

3.5 Project Management Plan

To ensure the high-quality and timely implementation of the dissertation, we developed a thorough Project Management Plan and adjusted throughout the duration of the project. This is as depicted in the Gantt Chart in Annex [A.3](#), which shows the key tasks and milestones of the dissertation.

During the design and execution of this work, we had regular weekly meetings with my supervisor, Prof. Andrew Wright, and discussed the scope and direction of the project, the scenarios to be modelled and the progress made. Most important, we reflected on various issues arising and sought solutions.

Some of the issues encountered were:

- Integrating the simulation of wind power into the main energy modelling tool, Polysun. This is discussed in more details in section 2.3.3. To overcome this problem, I developed a code in Python, that assembles and analyses data obtained from different sources, concerning photovoltaics, energy storage and wind turbines.
- Modelling of Demand Shaping Measures (DSM) was not possible in our energy modelling tool, therefore, DSM were neglected in our simulations.
- Modelling of energy sectors, beyond electricity generation and residential, notably modelling of transport, industry and agriculture, was very complex. Therefore, these sectors were not taken into consideration in our analysis.

The project run smoothly, in-line with the Project Management Plan. At the end of each task, the results were double-checked and the relevant part of the final report was drafted. One interim report and the final report were submitted in time.

4 Results

This section presents the performance of the net zero energy systems in the three scenarios, based on the simulation results and analysis. It seeks to evaluate the effectiveness and reliability of these systems in the residential sector.

Figure 4.1 depicts the average daily electricity generation from renewable energy sources, i.e. PV panels, wind turbine, and battery. The visualisation also includes the demand for electricity, provided by the simulation, in order to depict the full picture of demand and supply and identify the time periods when electricity has to be imported from the grid. The findings revealed that throughout the year, the community relied heavily on renewable sources of energy. The graph was generated based on the data acquired from the simulation of the first scenario.

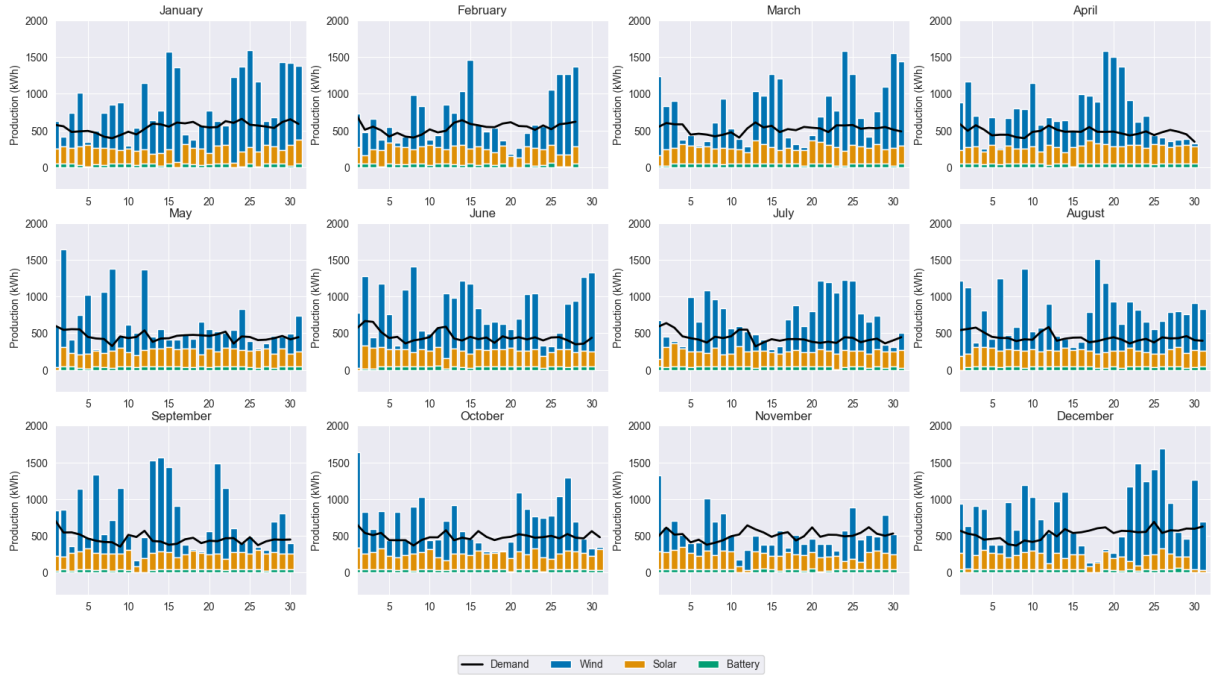
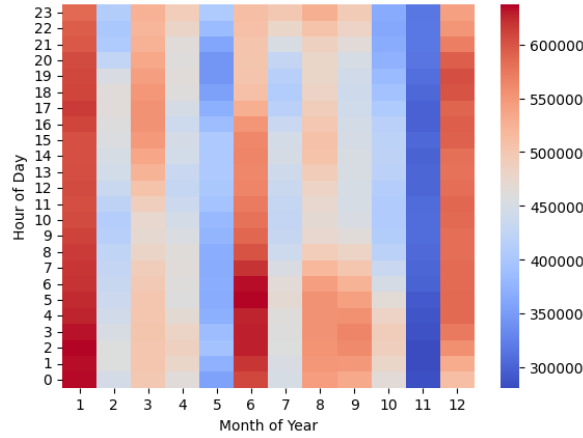


Figure 4.1: Daily average of electricity production and consumption of the community for each month of the year

Figure 4.2 presents a heatmap of the wind electricity production during the day, generated by the Seaborn program in Python. The heatmap is a data visualisation tool that displays the magnitude of wind electricity production in colours, with one column for each month of the year. The heatmap was very useful in understanding the time of day when wind energy production is strong and when it is relatively calm. The graph provides an overview of the monthly trends, and it can aid in forecasting the wind energy output. For example, the heatmap shows that in November, the community is expected to have no wind energy production for the entire month, as depicted in the previous Figure 4.1. This information is crucial in planning for the energy requirements of the community during that period, which will help to ensure a reliable and sustainable power supply.



Units: [W]

Figure 4.2: A heatmap of the wind generation during the hours of the day for each month

The graph gives us an overview of the wind intensity. For example, wind intensity tends to be higher during the early morning hours, from 0-8 am, with the exception of January and December; in June wind intensity reaches a peak in a short period of time, from 2 - 8 am, while in January, wind intensity remains constantly high. These data inform our simulations, as well as future predictions.

Solar thermal collectors efficiency

The energy system diagram for the thermal collectors linked to the household and the

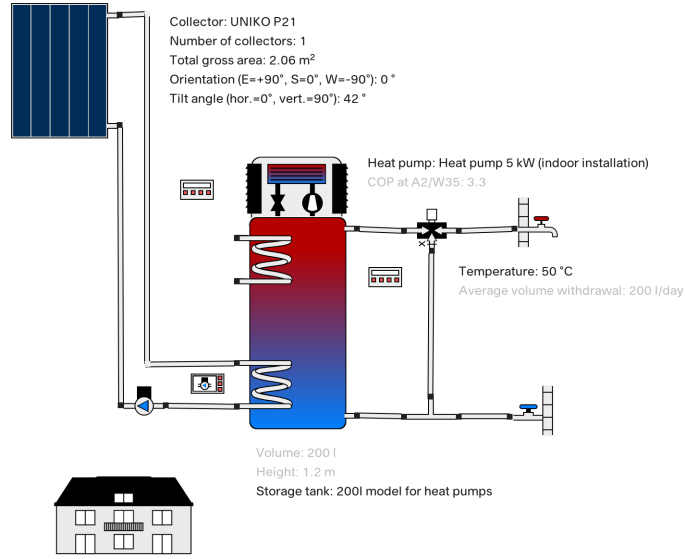


Figure 4.3: Diagram of thermal collector system in the house

grid is depicted in Figure 4.3. Only one collector for each house was used for this project since it demonstrated positive and efficient outcomes. Two pipes link the collector to a 200L water tank, which is suitable for a family of three individuals. Additionally, an indoor heat pump with a capacity of 5kW is installed to supply hot water during periods when the collector is insufficient. The pipe on the hot section of the tank is not in use, in this project, as it is designated solely for space heating. However, for our project, the Air Condition provides space heating.

The results of the simulation, in Figure 4.4, illustrate that the thermal collectors operate primarily from 8 am to 3 pm throughout the year, with a noticeable increase in irradiation during the summer months. Overall, thermal collectors are highly favoured in Greece, due to the region's location and the abundant solar irradiation throughout the year.

Solar thermal collector selection

Table 4.1 presents the simulation outcomes of the thermal collector system. Two simulations were conducted, one for a single collector and another for two collectors installed on the roof of each house. The results indicate that the solar fraction was higher when

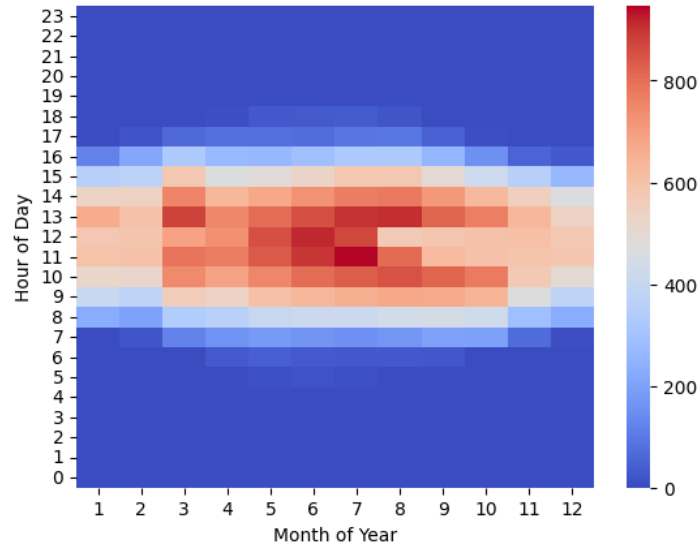


Figure 4.4: Hourly Solar irradiation onto collector [W/m^2]

two collectors were used as compared to only one collector, with solar fractions of 77.1% and 94.4%, respectively. This means that a considerable amount of the total energy for hot water was generated by the sun, resulting in savings in the total electricity consumption of the system.

Table 4.1: Results of the thermal energy system for scenario 1, 2 and 3

		1 collector		2 collectors	
		House	Com	House	Com
Fraction of solar energy to system	%	77.1		94.4	
Solar thermal energy to the system	kWh	2515	754500	3460	1038000
Heat generator energy to the system	kWh	735	220500	207	62100
Total energy consumption	kWh	2573	771900	2627	788100
Energy deficit	kWh	68.1	20430	27.0	8100
Total electricity consumption of the system	kWh	197	59100	55.8	16740

However, taking into consideration the costs, using just one solar collector per house is considered the optimal solution. Based on market research, the Pleion UNIKO P21 was selected as the most suitable option. With a high-efficiency rate of 94.5%, the Pleion UNIKO P21 can absorb and convert solar energy into hot water - at 50°C -, more effectively than other brands. Furthermore, the product has a lifespan of over 25 years, which is well above the industry standard, ensuring that the investment will provide long-term benefits.

4.1 Performance of Scenario 1

The first scenario was modelled to showcase the potential of an energy system with a remote solar farm. Figure 4.5 illustrates the energy system diagram, which incorporates a utility energy storage comprising 350 batteries of 3.685 kWh, a photovoltaic park with 5500 modules, resulting to total installed solar capacity of 2.47 MW and one wind turbine. Simulations indicated that one wind turbine is sufficient to power the community and four types of wind turbines, of varying power and hub heights, were simulated to compare results.

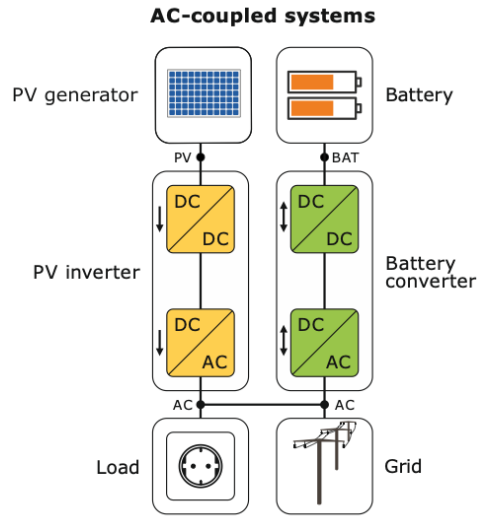


Figure 4.5: Polysun Dashboard for Scenario 1 and 2

1. Photovoltaics and battery storage

The Polysun simulations produced the following findings, shown in Table 4.2: results indicate that 44.1% of solar electricity generation was consumed directly by the community, without relying on energy storage.

2. Wind energy

Table 4.3 demonstrates the wind production and direct consumption for scenario 1, following the methodology explained above, and testing the system for four different wind turbines of varying capacity. While higher turbine capacity leads

Table 4.2: Results of the Photovoltaic panels and battery for scenario 1 and 3

PV capacity	MW	2.475
Battery capacity (only for scenario 1)	MWh	1.289
Yield Photovoltaics in AC	MWh	4168.1
Self-consumption	MWh	2062
To external grid	MWh	1595
From external grid	MWh	2215
Battery discharging energy	MWh	399
Total electricity consumption (in relation to grid)	MWh	508
Total electricity consumption	MWh	4676
CO2 savings	kg	2,235,783
Degree of self-sufficiency	%	44.1

to higher energy production, it is important to consider the associated costs to ensure that the investment is economically feasible.

Table 4.3: Results of Wind production for scenario 1

Manufacture		Gamesa G47	Gamesa G52	Vestas	Enercon E66
Hub height	<i>meter</i>	55	55	86	60
Turbine capacity	<i>kW</i>	660	850	850	1500
Wind yield	<i>MWh</i>	2027	2655	2748	4174
Self-consumption	<i>MWh</i>	986	1168	1197	1403.9

3. Key Observations

Based on the simulation results, I calculated the share of the different renewable energy sources and the grid to achieve the NZC target (Table 4.4). This enables the comparison between wind turbines -of different power - and the grid consumption, which inform the analysis and decision making in terms of self-sufficiency. The data reveals a trade off: an increase in wind turbine capacity results in a reduction of electricity consumption from grid. Specifically, low-power wind turbine (Gamesa G47) produces 21% of the total electricity consumption, resulting to a grid utilisation at 9.77%. In the same line, the high-power turbine (Enercon E66) produces 30% of the community electricity demand, minimising grid consumption to close-to-zero, 0.84%.

The solar park capacity has been adjusted to satisfy demand, thereby generating a constant 44.10% of total energy demand. The solar collector contribution is

Table 4.4: Overall of the Scenario 1

	Turbine Brands			
	Gamesa G47	Gamesa G52	Vestas	Enercon E66
Wind	21.09%	24.97%	25.61%	30.02%
PV	44.10%	44.10%	44.10%	44.10%
Collector	16,51%	16,51%	16,51%	16,51%
Battery	8.53%	8.53%	8.53%	8.53%
Grid	9.77%	5.89%	5.26%	0.84%

the same for all scenarios and amounts to 16.51% of total energy consumption. Battery output remains consistent at 8.53% across all wind turbine brands.

Overall, we observe that the first scenario of microgrid configuration is close to Net Zero, as it only imports from the national grid (in the best case of high-power wind turbine) 0.84% of the energy needed to serve the community's load.

4.2 Performance of Scenario 2

In the second scenario, the energy system employs distributed renewable energy technologies in each house. Photovoltaic panels with thermal collectors and one wall battery are installed in each house, while a wind turbine is installed for the entire community.

1. Photovoltaics and battery storage

Table 4.5 showcases the results of the simulation conducted for the PV system with one battery. The analysis indicates that the system has a lower percentage of self-sufficiency at 38.3% from PVs, meaning a smaller share of the total solar generation is consumed directly, without factoring in the charging of the batteries. This is a lower degree of self-sufficiency when compared to the solar park in scenario 1, but taking into account the difference in installed solar capacity is also smaller (1.35 MW vs 2.47 MW in scenario 1) and in PV yield (2193 MWh vs 4168 MWh in scenario 1), the degree of self-sufficiency is proportionally higher in scenario 2.

Table 4.5: Results of the Photovoltaic panels and battery for the second scenario

	Community	Per House
PV capacity	1.35 MW	4.5kW
Battery capacity	1.1MWh	3.68kW
Degree of self-sufficiency		38.3 %
Yield Photovoltaics AC	2192.94 MWh	7309.9 kWh
Self-consumption	1794.6 MWh	5982 kWh
To external grid	98.1 MWh	327 kWh
From external grid	2676.6 MWh	8922 kWh
Battery discharging energy	240.6 MWh	802 kWh
Total electricity consumption of the system	2482.8 MWh	8276 kWh
Total electricity consumption	4693.5 MWh	15645 kWh
CO2 savings	1176.3 t	3921 kg

To estimate the values for the entire community the values for each house have been multiplied by the number of houses in the community. According to Google Maps, the community comprises around 300 houses. The "Community" column provides an estimation of the total values for the entire community.

2. Wind energy

Table 4.6 displays the results of the simulations for four wind turbines of different capacities, ranging from 1.3 MW to 2 MW and installed at different hub heights, from 90m to 105m. Due to the low self-sufficiency of the PV system, it was necessary to increase the turbine capacity to meet the energy demands of the community.

Table 4.6: Results of wind generation from the turbines for scenario 2

Manufacture		Siemens	Vestas	Vestas	Vestas
Hub height	meter	90	78	80	105
Turbine capacity	kW	1300	1800	2000	2000
Wind yield	MWh	4090	6185	7474	7668
Self-consumption	MWh	2026	2295	2462	2505

3. Key observations

Table 4.7, presents the share of the different renewable energy technologies (RETs) to serve local loads.

Table 4.7: Overall of the Scenario 2

	Turbine Brands			
	Siemens	Vestas	Vestas	Vestas
Wind	43.17%	48.9%	52.47%	53.37%
PV	38.24%	38.24%	38.24%	38.24%
Collector	16,51%	16,51%	16,51%	16,51%
Battery	5.13%	5.13%	5.13%	5.13%
Grid	-3.04%	-8.77%	-12.34%	-13.24%

The second scenario was designed to assess the energy mix with focus on wind turbines of varying power. The rooftop PVs cover 38.24% of total electricity demand, while the solar collector contributes 16.51% and battery output is responsible for 5.13%. Wind turbines cover most of the local load, ranging from 43.17% for the low-power Siemens 1.3MW, to 53.37% for the high-power Vestas 2MW. The negative values for the grid contribution means that there is excess of local electricity production and it is fed into the grid.

Therefore, this proved to be a **Positive Energy Community** scenario, meaning it serves completely the community's total electricity demand and exports the remaining electricity to the main grid.

Additionally, increasing the wind turbine capacity can further enhance the positive energy that is returned to the grid. This implies that investing in higher-capacity wind turbines could be an effective strategy for achieving positive energy communities.

4.3 Performance of Scenario 3

The final scenario consists of a solar park, as in scenario 1, as this was found to have higher yield and direct consumption compared to rooftop PV installations. One Wind turbine was positioned outside the community to complement the electricity generation from the PV park.

What sets this scenario apart is the fact that it does not use any energy storage tech-

nology, meaning that the energy generated is used directly as it is produced. This was designed to assess the cost-efficiency of such system for the community, as lithium-ion batteries are still expensive, and provide only short-term solutions, therefore their integration into a renewable energy system can increase the overall cost.

1. Photovoltaics

A decision was made to keep the solar park configuration stable (same as in scenario 1). The reason is to

- a) facilitate a clear comparison between an PV system that utilises energy storage and one that does not;
- b) shift focus towards optimising the wind turbines.

2. Wind energy

Table 4.8 displays the outcomes of scenario 3, where wind turbines of four different brands were tested. The wind turbines had capacities ranging from 660 kW to 2MW, and were installed at hub heights from 55 to 80 meters.

Table 4.8: Results of wind generation for scenario 3

Manufacture		Vestas	Enercon	Siemens	Vestas
Hub height	meter	55	55	58	80
Turbine capacity	kW	660	900	1300	2000
Wind yield	MWh	2027.2	2244.5	3964.48	7474.3
Self-consumption	MWh	1125	1177	1629	2040

The results indicate that the high-power Vestas 2MW turbine produced the highest wind yield of 7474.3 MWh, resulting in a remarkable 268.8% increase from the 2027 MWh generated by the low-power Vestas 0.66MW turbine. It is interesting to note that the hub height of the turbines did not vary significantly between manufacturers, ranging between 55 and 80 meters. These findings suggest that increasing the capacity of wind turbines is an effective way of producing more renewable energy in the community.

3. Key observations

As shown in Table 4.9, the Vestas 2MW turbine produced the highest wind yield at 43.63% of total electricity demand, followed by Siemens 1.3MW at 34.84%, Enercon 0.9MW at 25.16%, and the lowest yield was observed from the Vestas 0.66MW turbine at 24.06%. Solar energy generation remained constant at 44.10% for all four brands, solar thermal accounted for 16.51%, while the contribution of electricity consumption is relatively low, ranging from 4.57% to 15.33% of the local load. The grid consumption is negatively correlated to the power of wind turbines. increased, to reach **positive energy** when the most powerful Vestas 2MW turbine was used.

Table 4.9: Overall of the Scenario 3

	Turbine Brands			
	Vestas	Enercon	Siemens	Vestas
Wind	24.06%	25.16%	34.84%	43.63%
PV	44.10%	44.10%	44.10%	44.10%
Collector	16,51%	16,51%	16,51%	16,51%
Grid	15.33%	14.23%	4.57%	-4.23%

Overall, the third scenario is approaching Net Zero, but not as close as the scenarios 1 and 2. The only exception is when the high-power, Vestas 2MW turbine is used, and then this scenario offers a Positive Energy Model, feeding 4.23% to the external grid.

4.4 Analysis of economic viability

Achieving the net-zero transition requires significant investments. Hence a thorough financial assessment is necessary to assess the economic viability of the three scenarios, and compare the investments needed. This section provides an economic analysis of the three energy systems, with the objective to determine their financial viability. The following terms and indicators are used for the assessment:

1. **Capital expenditure** (CapEx) represents the total cost of acquiring and in-

stalling the necessary equipment for each energy system. This includes the cost of wind turbines, photovoltaic panels, and batteries. (Fig. 4.6)

2. **Operational expenditure** (OpEx) refers to the ongoing costs associated with maintaining and operating the energy systems, such as repairs, maintenance, and personnel. (Fig. 4.6)
3. **Profitability** is an important consideration in this project, and the community can make a profit by selling excess electricity back to the grid while also purchasing electricity from the grid when renewable energy technologies are not generating sufficient electricity to meet the community's demand. The balance between buying and selling electricity will ultimately determine the overall profitability of the project.
4. **Net present value** (NPV) represents the present value of future cash flows, discounted at a specific rate. A positive NPV indicates that the project is expected to generate a profit over its lifetime, while a negative NPV suggests that the project will result in a net loss.
5. **Payback period** represents the length of time required for the initial investment to be recouped through the profits generated by the project. A shorter payback period is generally desirable, as it means that the project will start generating profits sooner.
6. **Load** refers to the amount of electricity required by the community. The energy system must be designed to meet this load to ensure that the community's energy needs are met.

The economic evaluation of each investment depends on different parameters, including estimates for costs of different technologies and products, wholesale electricity prices and the discount rate. It also takes into account the cost of two types of wind turbines, out of the four simulated: the one of the lowest power and the one of the highest power. This enables comparison and identification of the most cost-efficient type of

wind turbine for the proposed energy system, taking into consideration factors such as its initial investment, operational and maintenance costs and its efficiency.

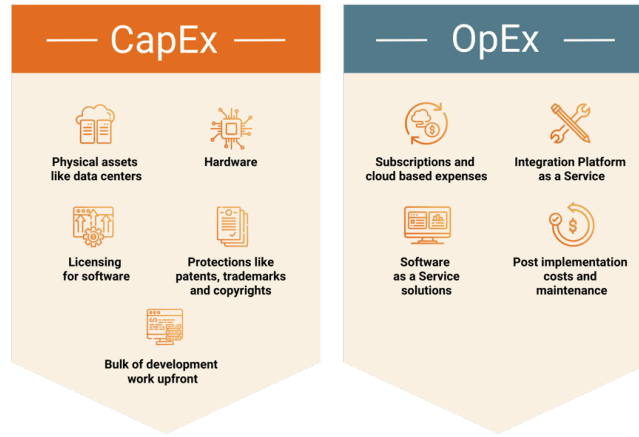


Figure 4.6: CAPEX and OPEX definitions, *source:[31]*

4.4.1 CapEx

Tables 4.10, 4.11 and 4.12 present the calculations of the initial investments for each scenario. The average price for the various modules of the energy system was obtained from the following sources:

1. The cost of the battery Li-ion from the Energy Storage Database and Use Case Matrix [32]
2. The cost of PV and wind turbines was based on the IRENA report on "Renewable power generation costs in 2021" [33]
3. The cost of the collector and the tank was taken from the official collector company website [34]

Table 4.10: CapEx for scenario 1

	Battery	PV	Wind (lp)	Wind (hp)	Collector + tank	Total CapEx
Capacity	1,290 kWh	2,475 kW	660 kW	1,500 kW	1 collector & 200L tank	
Avg price	345 €/kWh	663 €/kW	1,250 €/kW	1,250 €/kW	2344.55 €	
Avg CapEx (lp)	€ 445.0 K	€ 1,641.5 K	€ 825.0 K		€ 703.4 K	€ 3,614.8 K
Avg CapEx (hp)				€ 1,875.0 K		€ 4,664.8 K

Table 4.11: CapEx for scenario 2

	Battery	PV	Wind (lp)	Wind (hp)	Collector + tank	Total CapEx
Capacity	1,104 kWh	1,350 kW	1,300 kW	2,000 kW	1 collector & 200L tank	
Avg price	345 €/kWh	663 €/kW	1,250 €/kW	1,250 €/kW	2344.55 €	
Avg CapEx (lp)	€ 380.9 K	€ 895.3 K	€ 1,625.0 K		€ 703.4 K	€ 3,604.6 K
Avg CapEx (hp)				€ 2,500.0 K		€ 4,479.6 K

Table 4.12: CapEx for scenario 3

	Battery	PV	Wind (lp)	Wind (hp)	Collector + tank	Total CapEx
Capacity	0 kWh	2,475 kW	660 kW	2,000 kW	1 collector & 200L tank	
Avg price	345 €/kWh	663 €/kW	1,250 €/kW	1,250 €/kW	2344.55 €	
Avg CapEx (lp)	€ 0.0 K	€ 1,641.5 K	€ 825.0 K		€ 703.4 K	€ 3,169.8 K
Avg CapEx (hp)				€ 2,500.0 K		€ 4,844.8 K

Comparing the three scenarios, the most economic investment was the scenario 3 with the lowest-power wind turbine and with no energy storage. Nevertheless, scenario 3 with the highest-power wind turbine of 2MW, represents the most expensive investment. The trend implies that CAPEX will be decreasing through the years, thanks to technological achievements that offer more resilient, reliable and cost-efficient RETs.

4.4.2 Operation and Maintenance costs (OpEx)

O&M services are an important part of the energy system, that warranties its optimal function during its entire lifetime. OpEx is variable depending on each RET, because it depends on the technology, material, size and maintenance processes. Tables 4.13, 4.14 and 4.15 present the approximate values of the OpEx, obtained from the European Commission [35].

Table 4.13: OpEx for scenario 1

	Battery	PV	Wind (lp)	Wind (hp)	Collector + tank	Total OpEx
Avg price	0.5% / CapEx	9.1 €/kW	4.4% / CapEx	4.4% / CapEx		
Avg OpEx (lp)	€ 2.2 K	€ 22.5 K	€ 36.3 K	- €	- €	€ 61.0 K
Avg OpEx (hp)	€ 2.2 K	€ 22.5 K	- €	€ 82.5 K	- €	€ 107.2 K

Table 4.14: OpEx for scenario 2

	Battery	PV	Wind (lp)	Wind (hp)	Collector + tank	Total OpEx
Avg price	0.5% / CapEx	9.1 €/kW	4.4% / CapEx	4.4% / CapEx		
Avg OpEx (lp)	€ 1.9 K	€ 12.3 K	€ 71.5 K	- €	- €	€ 85.7 K
Avg OpEx (hp)	€ 1.9 K	€ 12.3 K	- €	€ 110.0 K	- €	€ 124.2 K

Table 4.15: OpEx for scenario 3

	Battery	PV	Wind (lp)	Wind (hp)	Collector + tank	Total OpEx
Avg price	0.5% / CapEx	9.1 €/kW	4.4% / CapEx	4.4% / CapEx		
Avg OpEx (lp)	- €	€ 22.5 K	€ 36.3 K	- €	- €	€ 58.8 K
Avg OpEx (hp)	- €	€ 22.5 K	- €	€ 110.0 K	- €	€ 132.5 K

4.4.3 Net Present Value, Benefit-Cost analysis and Payback Period

The transition towards a net zero economy is the only option for a sustainable future, but it requires significant investments in technology and infrastructure. The environmental and social benefits are enormous, such as emissions reduction, deceleration of global warming, health improvement, more liveable cities and communities, more and greener jobs and reduced energy bills. Although these benefits are the most important and should weight heavily in the evaluation of clean-tech investments, in practice, their quantitative/economic assessment is impossible, due to lack of reliable economic and metrics. Therefore, the investment viability assessment does not account for the environmental and social benefits.

For the economic analysis, the fluctuating electricity prices, due the Russian war in Ukraine and the subsequent energy crisis, made it challenging to accurately factor-in average electricity prices for trading with the external grid. The electricity monthly statistics revealed unusually high numbers in 2022, going three to five times higher than the previous years. The peak in electricity prices and the uncertainty about the end of the war and the new energy landscape, was a crucial issue, for predicting the

cost of purchasing electricity from the grid and the benefits of selling energy back to the grid in the coming months and years.

The estimated price of electricity bought from the grid is 244€ per MWh or 0.224€ per kWh [36], as indicated in tables 4.16, 4.17 and 4.18. It's important to note that this price applies only to households and not the industrial and commercial sectors.

The cost of selling to the grid is determined through contractual agreements, so called Power Purchase Agreements (PPAs) between the renewable energy producers (individuals or companies) and the country's electricity companies. In April 2023, a new regulation was adopted in Greece, stipulating that the selling price for solar energy would be 69€ per MWh for a 7-year contract, while for wind turbines, it would be 80€ per MWh [37]. Hence these values were used in our calculations for the investment viability.

Table 4.16: Annual trade with the grid - Scenario 1

Benefits (selling to the grid)					
	PV	Wind (lp)	Wind (hp)	Total	
Energy to the grid	1,595 MWh	1,041.14 MWh	2,770 MWh	PV + wind lp	PV + wind hp
Avg price	69 €/MWh	80 €/MWh	80 €/MWh		
Yearly	€ 110.1 K	€ 83.3 K	€ 221.6 K	€ 193.1 K	€ 331.7 K
Expense (buying from the grid)					
		Wind (lp)	Wind (hp)	Total	
Energy from grid		1,229 MWh	811 MWh	PV + wind lp	PV + wind hp
Electricity price (S2 2022)		244 €/MWh	244 €/MWh		
Yearly		299,710 €	197,836 €	€ 299.7 K	€ 197.8 K

Table 4.17: Annual trade with the grid - Scenario 2

Benefits (selling to the grid)					
	PV	Wind (lp)	Wind (hp)	Total	
Energy to the grid	98 MWh	2,063.47 MWh	5,000 MWh	PV + wind lp	PV + wind hp
Avg price	87 €/MWh	80 €/MWh	80 €/MWh		
Yearly	€ 8.5 K	€ 165.1 K	€ 400.0 K	€ 173.6 K	€ 408.5 K
Expense (buying from the grid)					
		Wind (lp)	Wind (hp)	Total	
Energy from grid		1,067 MWh	666 MWh	PV + wind lp	PV + wind hp
Electricity price (S2 2022)		243.8 €/MWh	243.8 €/MWh		
Yearly		€ 260.1 K	€ 162.4 K	€ 260,1 K	€ 162,4 K

Table 4.18: Annual Trade with the grid - Scenario 3

Benefits (selling to the grid)					
	PV	Wind (lp)	Wind (hp)	Total	
Energy to the grid	2,106 MWh	902.09 MWh	5,434 MWh	PV + wind lp	PV + wind hp
Avg price	€ 69	80 €	80 €		
Yearly	€ 145.3 K	€ 72.2 K	€ 434.7 K	€ 217.5 K	€ 580.0 K
Expense (buying from the grid)					
		Wind (lp)	Wind (hp)	Total	
Energy from grid		1,489 MWh	574 MWh	PV + wind lp	PV + wind hp
Electricity price (S2 2022)		243.8 €	243.8 €		
Yearly		€ 363.1 K	€ 140.0 K	€ 363.1 K	€ 140.0 K

The NPV of the costs for each scenario over 20 years, the benefit-cost ratio of the investment and the discounted payback periods are calculated in Tables 4.19, 4.20 and 4.21 with a discount rate of 4%.

Table 4.19: Investment viability for Scenario 1

Year	Cash Flow			Discounted Cash Flow			Savings		Discounted Pay-Back Period
	100 % from Grid	All (wind lp)	All (wind hp)	100 % from Grid	All (wind lp)	All (wind hp)	All (wind lp)	All (wind hp)	
0	0	€ 3.614,8 K	€ 4.664,8 K		€ 3.614,8 K	€ 4.664,8 K	-€ 3.614,8 K	-€ 4.664,8 K	
1	€ 1.140,0 K	€ 167,4 K	-€ 26,6 K	€ 1.096,2 K	€ 161,0 K	-€ 25,6 K	€ 935,2 K	€ 1.121,7 K	All (wind hp) -5th Y: € 5193,5 K
2	€ 1.140,0 K	€ 167,4 K	-€ 26,6 K	€ 1.054,0 K	€ 154,8 K	-€ 24,6 K	€ 899,2 K	€ 1.078,6 K	
3	€ 1.140,0 K	€ 167,4 K	-€ 26,6 K	€ 1.013,5 K	€ 148,8 K	-€ 23,6 K	€ 864,6 K	€ 1.037,1 K	
4	€ 1.140,0 K	€ 167,4 K	-€ 26,6 K	€ 974,5 K	€ 143,1 K	-€ 22,7 K	€ 831,4 K	€ 997,2 K	All (wind lp) - 5th Y: € 4329,9 K
5	€ 1.140,0 K	€ 167,4 K	-€ 26,6 K	€ 937,0 K	€ 137,6 K	-€ 21,8 K	€ 799,4 K	€ 958,9 K	
6	€ 1.140,0 K	€ 167,4 K	-€ 26,6 K	€ 901,0 K	€ 132,3 K	-€ 21,0 K	€ 768,7 K	€ 922,0 K	
7	€ 1.140,0 K	€ 167,4 K	-€ 26,6 K	€ 866,3 K	€ 127,2 K	-€ 20,2 K	€ 739,1 K	€ 886,5 K	
8	€ 1.140,0 K	€ 167,4 K	-€ 26,6 K	€ 833,0 K	€ 122,3 K	-€ 19,4 K	€ 710,7 K	€ 852,4 K	
9	€ 1.140,0 K	€ 167,4 K	-€ 26,6 K	€ 801,0 K	€ 117,6 K	-€ 18,7 K	€ 683,3 K	€ 819,6 K	
10	€ 1.140,0 K	€ 167,4 K	-€ 26,6 K	€ 770,2 K	€ 113,1 K	-€ 18,0 K	€ 657,1 K	€ 788,1 K	
11	€ 1.140,0 K	€ 167,4 K	-€ 26,6 K	€ 740,5 K	€ 108,7 K	-€ 17,3 K	€ 631,8 K	€ 757,8 K	
12	€ 1.140,0 K	€ 167,4 K	-€ 26,6 K	€ 712,1 K	€ 104,6 K	-€ 16,6 K	€ 607,5 K	€ 728,7 K	
13	€ 1.140,0 K	€ 167,4 K	-€ 26,6 K	€ 684,7 K	€ 100,5 K	-€ 16,0 K	€ 584,1 K	€ 700,6 K	
14	€ 1.140,0 K	€ 167,4 K	-€ 26,6 K	€ 658,3 K	€ 96,7 K	-€ 15,4 K	€ 561,7 K	€ 673,7 K	
15	€ 1.140,0 K	€ 167,4 K	-€ 26,6 K	€ 633,0 K	€ 93,0 K	-€ 14,8 K	€ 540,1 K	€ 647,8 K	
16	€ 1.140,0 K	€ 167,4 K	-€ 26,6 K	€ 608,7 K	€ 89,4 K	-€ 14,2 K	€ 519,3 K	€ 622,9 K	
17	€ 1.140,0 K	€ 167,4 K	-€ 26,6 K	€ 585,3 K	€ 85,9 K	-€ 13,6 K	€ 499,3 K	€ 598,9 K	
18	€ 1.140,0 K	€ 167,4 K	-€ 26,6 K	€ 562,7 K	€ 82,6 K	-€ 13,1 K	€ 480,1 K	€ 575,9 K	
19	€ 1.140,0 K	€ 167,4 K	-€ 26,6 K	€ 541,1 K	€ 79,5 K	-€ 12,6 K	€ 461,6 K	€ 553,7 K	
20	€ 1.140,0 K	€ 167,4 K	-€ 26,6 K	€ 520,3 K	€ 76,4 K	-€ 12,1 K	€ 443,9 K	€ 532,4 K	
Net Present Value				€ 15.493,3 K	€ 5.890,0 K	€ 4.303,5 K	€ 9.603,3 K	€ 11.189,7 K	Total Saving
Total savings per household							€ 32,0 K	€ 37,3 K	
Benefit - cost ratio = SUM of savings/Investment							3,66	3,40	€ 11.189,7 K

Table 4.20: Investment viability for Scenario 2

Year	Cash Flow			Discounted Cash Flow			Savings		Discounted Pay-Back Period
	100% from Grid	All (wind lp)	All (wind hp)	100% from Grid	All (wind lp)	All (wind hp)	All (wind lp)	All (wind hp)	
0	€ 0,0 K	€ 3.604,6 K	€ 4.479,6 K		€ 3.604,6 K	€ 4.479,6 K	-€ 3.604,6 K	-€ 4.479,6 K	
1	€ 1.140,0 K	€ 172,2 K	-€ 121,9 K	€ 1.096,2 K	€ 165,6 K	-€ 117,3 K	€ 930,6 K	€ 1.213,4 K	All (wind hp) -4th Y: € 4580,8 K
2	€ 1.140,0 K	€ 172,2 K	-€ 121,9 K	€ 1.054,0 K	€ 159,2 K	-€ 112,7 K	€ 894,8 K	€ 1.166,8 K	
3	€ 1.140,0 K	€ 172,2 K	-€ 121,9 K	€ 1.013,5 K	€ 153,1 K	-€ 108,4 K	€ 860,4 K	€ 1.121,9 K	
4	€ 1.140,0 K	€ 172,2 K	-€ 121,9 K	€ 974,5 K	€ 147,2 K	-€ 104,2 K	€ 827,3 K	€ 1.078,7 K	All (wind lp) -5th Y: € 4308,6 K
5	€ 1.140,0 K	€ 172,2 K	-€ 121,9 K	€ 937,0 K	€ 141,5 K	-€ 100,2 K	€ 795,5 K	€ 1.037,2 K	
6	€ 1.140,0 K	€ 172,2 K	-€ 121,9 K	€ 901,0 K	€ 136,1 K	-€ 96,4 K	€ 764,9 K	€ 997,4 K	
7	€ 1.140,0 K	€ 172,2 K	-€ 121,9 K	€ 866,3 K	€ 130,8 K	-€ 92,7 K	€ 735,5 K	€ 959,0 K	
8	€ 1.140,0 K	€ 172,2 K	-€ 121,9 K	€ 833,0 K	€ 125,8 K	-€ 89,1 K	€ 707,2 K	€ 922,1 K	
9	€ 1.140,0 K	€ 172,2 K	-€ 121,9 K	€ 801,0 K	€ 121,0 K	-€ 85,7 K	€ 680,0 K	€ 886,6 K	
10	€ 1.140,0 K	€ 172,2 K	-€ 121,9 K	€ 770,2 K	€ 116,3 K	-€ 82,4 K	€ 653,8 K	€ 852,5 K	
11	€ 1.140,0 K	€ 172,2 K	-€ 121,9 K	€ 740,5 K	€ 111,9 K	-€ 79,2 K	€ 628,7 K	€ 819,8 K	
12	€ 1.140,0 K	€ 172,2 K	-€ 121,9 K	€ 712,1 K	€ 107,5 K	-€ 76,2 K	€ 604,5 K	€ 788,2 K	
13	€ 1.140,0 K	€ 172,2 K	-€ 121,9 K	€ 684,7 K	€ 103,4 K	-€ 73,2 K	€ 581,3 K	€ 757,9 K	
14	€ 1.140,0 K	€ 172,2 K	-€ 121,9 K	€ 658,3 K	€ 99,4 K	-€ 70,4 K	€ 558,9 K	€ 728,8 K	
15	€ 1.140,0 K	€ 172,2 K	-€ 121,9 K	€ 633,0 K	€ 95,6 K	-€ 67,7 K	€ 537,4 K	€ 700,7 K	
16	€ 1.140,0 K	€ 172,2 K	-€ 121,9 K	€ 608,7 K	€ 91,9 K	-€ 65,1 K	€ 516,7 K	€ 673,8 K	
17	€ 1.140,0 K	€ 172,2 K	-€ 121,9 K	€ 585,3 K	€ 88,4 K	-€ 62,6 K	€ 496,9 K	€ 647,9 K	
18	€ 1.140,0 K	€ 172,2 K	-€ 121,9 K	€ 562,7 K	€ 85,0 K	-€ 60,2 K	€ 477,7 K	€ 622,9 K	
19	€ 1.140,0 K	€ 172,2 K	-€ 121,9 K	€ 541,1 K	€ 81,7 K	-€ 57,9 K	€ 459,4 K	€ 599,0 K	
20	€ 1.140,0 K	€ 172,2 K	-€ 121,9 K	€ 520,3 K	€ 78,6 K	-€ 55,7 K	€ 441,7 K	€ 575,9 K	
Net Present Value				€ 15.493,3 K	€ 5.944,7 K	€ 2.822,3 K	€ 9.548,6 K	€ 12.671,0 K	Total Saving
Total savings per household							€ 31,8 K	€ 42,2 K	
Benefit - cost ratio = SUM of savings/Investment							3,65	3,83	€ 12.671,0 K

Table 4.21: Investment viability for Scenario 3

Year	Cash Flow			Discounted Cash Flow			Savings		Discounted Pay-Back Period
	100% from Grid	All (wind lp)	All (wind hp)	100% from Grid	All (wind lp)	All (wind hp)	All (wind lp)	All (wind hp)	
0	€ 0,0 K	€ 3.169,8 K	€ 4.844,8 K		€ 3.169,8 K	€ 4.844,8 K	-€ 3.169,8 K	-€ 4.844,8 K	
1	€ 1.140,0 K	€ 204,4 K	-€ 307,5 K	€ 1.096,2 K	€ 196,6 K	-€ 295,7 K	€ 899,6 K	€ 1.391,9 K	All (wind hp) -4th Y: € 5254,4 K
2	€ 1.140,0 K	€ 204,4 K	-€ 307,5 K	€ 1.054,0 K	€ 189,0 K	-€ 284,3 K	€ 865,0 K	€ 1.338,3 K	
3	€ 1.140,0 K	€ 204,4 K	-€ 307,5 K	€ 1.013,5 K	€ 181,7 K	-€ 273,4 K	€ 831,7 K	€ 1.286,9 K	
4	€ 1.140,0 K	€ 204,4 K	-€ 307,5 K	€ 974,5 K	€ 174,7 K	-€ 262,9 K	€ 799,7 K	€ 1.237,4 K	All (wind lp) -4th Y: € 3396,1 K
5	€ 1.140,0 K	€ 204,4 K	-€ 307,5 K	€ 937,0 K	€ 168,0 K	-€ 252,8 K	€ 769,0 K	€ 1.189,8 K	
6	€ 1.140,0 K	€ 204,4 K	-€ 307,5 K	€ 901,0 K	€ 161,6 K	-€ 243,0 K	€ 739,4 K	€ 1.144,0 K	
7	€ 1.140,0 K	€ 204,4 K	-€ 307,5 K	€ 866,3 K	€ 155,4 K	-€ 233,7 K	€ 711,0 K	€ 1.100,0 K	
8	€ 1.140,0 K	€ 204,4 K	-€ 307,5 K	€ 833,0 K	€ 149,4 K	-€ 224,7 K	€ 683,6 K	€ 1.057,7 K	
9	€ 1.140,0 K	€ 204,4 K	-€ 307,5 K	€ 801,0 K	€ 143,6 K	-€ 216,1 K	€ 657,3 K	€ 1.017,0 K	
10	€ 1.140,0 K	€ 204,4 K	-€ 307,5 K	€ 770,2 K	€ 138,1 K	-€ 207,8 K	€ 632,1 K	€ 977,9 K	
11	€ 1.140,0 K	€ 204,4 K	-€ 307,5 K	€ 740,5 K	€ 132,8 K	-€ 199,8 K	€ 607,7 K	€ 940,3 K	
12	€ 1.140,0 K	€ 204,4 K	-€ 307,5 K	€ 712,1 K	€ 127,7 K	-€ 192,1 K	€ 584,4 K	€ 904,1 K	
13	€ 1.140,0 K	€ 204,4 K	-€ 307,5 K	€ 684,7 K	€ 122,8 K	-€ 184,7 K	€ 561,9 K	€ 869,4 K	
14	€ 1.140,0 K	€ 204,4 K	-€ 307,5 K	€ 658,3 K	€ 118,1 K	-€ 177,6 K	€ 540,3 K	€ 835,9 K	
15	€ 1.140,0 K	€ 204,4 K	-€ 307,5 K	€ 633,0 K	€ 113,5 K	-€ 170,8 K	€ 519,5 K	€ 803,8 K	
16	€ 1.140,0 K	€ 204,4 K	-€ 307,5 K	€ 608,7 K	€ 109,1 K	-€ 164,2 K	€ 499,5 K	€ 772,9 K	
17	€ 1.140,0 K	€ 204,4 K	-€ 307,5 K	€ 585,3 K	€ 104,9 K	-€ 157,9 K	€ 480,3 K	€ 743,1 K	
18	€ 1.140,0 K	€ 204,4 K	-€ 307,5 K	€ 562,7 K	€ 100,9 K	-€ 151,8 K	€ 461,8 K	€ 714,5 K	
19	€ 1.140,0 K	€ 204,4 K	-€ 307,5 K	€ 541,1 K	€ 97,0 K	-€ 146,0 K	€ 444,1 K	€ 687,1 K	
20	€ 1.140,0 K	€ 204,4 K	-€ 307,5 K	€ 520,3 K	€ 93,3 K	-€ 140,3 K	€ 427,0 K	€ 660,6 K	
Net Present Value				€ 15.493,3 K	€ 5.948,1 K	€ 665,5 K	€ 9.545,1 K	€ 14.827,7 K	Total Saving
Total savings per household							€ 31,8 K	€ 49,4 K	
Benefit - cost ratio = SUM of savings/Investment							4,01	4,06	€ 14.827,7 K

The **NPV of total savings** for a lifetime of 20 years, amount from € 11.19 million for the first scenario, to € 12.67 million for the second scenario and € 14.82 million for the third. This indicates that **the third scenario is the most economically profitable energy system, probably driven by the absence of high-cost lithium-ion batteries.**

The **benefit-cost ratios** are all much higher than 1 in all three scenarios, ranging from 3.65 to 4.06, which makes all investments economically profitable. **The third scenario**

provides the best benefit-cost ratio of 4.06.

The **payback periods** for the three scenarios range from 3.35 to 4 years (Table 4.22), which are very low. This indicator however, is not the preferred option for investment assessment, as it does not account for the savings beyond the payback period.

Table 4.22: Pay-back period for scenario 1

	All (wind lp)	All (wind hp)
Scenario 1	3,72 years	4,00 years
Scenario 2	3,72 years	3,55 years
Scenario 3	3,39 years	3,35 years

The **discounted Payback periods** for each scenario, considering the net present worth of costs and savings, ranges between the 4th year for the third scenario to the 5th year for the first and second scenarios, which makes the investment in all cases very interesting.

5 Discussion

The energy modelling experiments unveiled the following observations that deserve further discussion in the future. In addition, this chapter outlines the future trends in technology developments and costs. It also summarises the key challenges that need to be taken into consideration to deploy efficient and cost-effective microgrids to power a net zero energy community.

5.1 Observations

There is no one optimal solution for all situations. The choice of the optimal solution depends on one hand on parameters such as geographic location, weather conditions, local load, and on the other hand on the objective one wishes to achieve, namely maximising self-sufficiency, resilience and reliability of the microgrid; going beyond Net Zero towards Positive Energy Communities; and cost-efficiency:

1. **Optimisation of Self-sufficiency: From net-zero towards a Positive Energy Community.** Based on the simulation results, **the second Scenario**, which involves a distributed energy system with PVs and lithium-ion batteries in each house, and a wind turbine at community level, is the optimal microgrid configuration that is suitable for a **Positive Energy Community**. With all types of wind turbines, the community load was entirely covered by renewables and the excess electricity was fed to the main grid. However, all scenarios obtained very good results.

Further experimentation and fine-tuning, with more advanced energy modelling tools, would help understand better the correlation among the different components of these configurations. However, this was not possible within the scope of this dissertation.

2. **Optimisation of Economic Viability:** The third scenario with the high-power wind turbine, but without energy storage, **the third scenario is the most economically viable energy system, driven by the absence of high-cost lithium-ion batteries.** Scenario 3 presents the highest CAPEX of € 4.8 million, driven by the wind turbine prices, and OPEX at € 132.5 K, but also the highest return on investment at € 14.8 million over 20 years. This is also a positive energy scenario, with **the highest benefit-cost ratio of 4.06** which makes the investment highly profitable.

On the other end, **the second scenario, which is a Positive Energy Scenario, and the optimal solution in terms of energy performance** presents the lowest CAPEX of € 3.6 million, but also the **lowest return on investment** at € 9.54 million for the configuration with the lowest wind turbine. The benefit-cost ratio ranges from 3.5 to 3.83, making the investment highly profitable.

The first scenario, which uses the higher capacity PV park, energy storage, and wind turbine, presents a medium return on investment at € 9.6 million for the configuration with the low-power wind turbine to € 11.2 million for the high-power turbine. The benefit-cost ratio is also very high, ranging from 3.4 to 3.66.

These findings call for further research into the potential role of high power wind turbines in microgrids, as it could counterbalance the solar power supply and decrease the investments in costly batteries.

5.2 Future trends

1. **Energy efficiency is improving and energy demand is decreasing rapidly.** The assessment by the European Commission of the national energy and climate plans suggests that if all national commitments are fulfilled, the total share of RES will be between 33.1% and 33.7% by 2030, meeting the 32% target set by the EC in 2020. Additionally, between 2005 and 2020, 24 EU countries showed a decrease in final energy consumption, with the most significant reductions observed in

Greece, Italy, Portugal, and Spain, where the decrease ranged between 21% and 31%. [38]

Conversely, only three countries - Lithuania, Malta, and Poland - showed an increase in final energy consumption during the COVID-19 pandemic. This rise was mainly due to a substantial surge in transport demand in Lithuania (53%), Malta (23%), and Poland (78%), as well as growth in the services sector in Malta (93%). The other countries showed a decrease in their final energy consumption. [39].

2. **Clean technologies are becoming more powerful and cost-efficient, making the investments towards Net-Zero, economically, environmentally, and socially justifiable.** Globally, the cost of installing solar PV projects is expected to decline significantly over the next 30 years. By 2030, the average cost is projected to range from \$340 to \$834/kW, while by 2050 it is expected to drop to \$165 to \$481/kW, compared to an average of \$1210/kW in 2018 [40].

Utility-scale PV systems' global weighted average capacity factor has been increasing due to more significant deployment in regions with higher irradiation levels, the use of tracking systems, and improved system performance, material, technology, and inverter efficiency. This increase in capacity factor, combined with the rapid decline in installation costs, has made solar PV more economically competitive worldwide [41].

The average Levelized Cost of Electricity (LCOE) of utility-scale PV plants has decreased by 77% from around \$0.37/kWh in 2010 to \$0.085/kWh in 2018. Auction and tender results suggest that this trend will continue, with LCOE falling to between \$0.08/kWh and \$0.02/kWh by 2030. [40]

5.3 Challenges

There are several issues mostly related to reliability in microgrids for NZC, namely:

1. **Limitations of energy modelling tools:** Traditional modelling tools like Polysun, are limited and even unsuitable for the simulation of microgrids and the combined integration of diverse decentralised renewable sources, like solar and wind technologies and energy storage systems. In addition, modelling Demand Shaping Measures and the factoring in the energy consumption of other sectors, notably transport, industry and agriculture, is very complex. This calls for further research and development of more sophisticated tools in this field.
2. **Reliability of Distributed Energy Resources (DER):** Microgrids consist mainly of renewables, whose intermittent nature requires careful planning and management to ensure reliable operation. Those are complex systems that require sophisticated **control and monitoring, protection and switching systems** that can monitor, detect and isolate faults in order to continuously balance supply and demand in real-time, and ensure the microgrid stability. In addition, they also require regular **Operations, Maintenance and Repair (OMR)** service, including inspections of equipment and infrastructure, as well as timely repairs and replacements of components when needed. Overall, ensuring the stability and reliability of microgrids requires careful planning, design, and management and continuous monitoring to address any issues that arise.
3. **Cybersecurity:** Microgrids are vulnerable to cyber attacks, which can compromise their reliability and security. This is particularly concerning as microgrids become more connected and integrated with other energy systems and the larger grid.
4. **Awareness and Education:** Raising awareness among citizens and professionals about the importance of decarbonization and educating them on energy-efficient practices, the benefits of using renewable energy, and the overall impact of their consumption choices on climate change, can drive behavioural change and support the NZC transition.

6 Conclusions & Recommendations

Research work on Net Zero Community (NZC) has started emerging and is cutting across different disciplines, including energy engineering, as well as civil, mechanical, transport and agriculture engineering. This project carried out desk research, modelling, simulation, and analysis of various microgrid configurations with the aim to develop a framework for evaluation and identification of an optimal NZC for the community of Palecastro, in Crete. The research findings concluded that:

- Designing and implementing a NZC requires a holistic approach involving a combination of strategies and investments, including energy efficiency measures; integration of renewables and low-carbon technologies in local power generation, through smart microgrids; decarbonisation of buildings, electrification of transport and industry; and investments in smart, interconnected grid infrastructure.
- Determining the optimal energy system for a specific NZC, depends on many parameters, such as location, weather conditions, local load, reliability and resilience of the microgrid, and expected return on investment.
- Improving energy efficiency is the utmost priority for a successful transition and long-lasting results. This requires Demand Shaping Measures, as well as public engagement, and citizen behaviour change.
- A localised Distributed Energy System, involving rooftop PVs and lithium-ion batteries in each house, and a wind turbine at community level, is the optimal microgrid configuration, in terms of self-sufficiency and Positive Energy Community.
- The most economically profitable microgrid combines a PV park and high-power wind turbine at community level, but without energy storage, which increases

significantly the cost of the system.

- The "Cost of No-Action" is always higher than any net zero scenario.
- The most important are the environmental and social benefits of the NZC transition and they justify fully the high investments required, even though these benefits cannot be accurately measured in economic terms.
- The fact that clean technologies are improving at fast pace while costs are falling, paves the way for accelerated net zero transition until 2050.

Further research challenges are identified, in the field of microgrid reliability and cybersecurity; and on optimisation of energy modelling tools, that would enable simulating more complex microgrids with combined distributed renewable energy sources and energy storage systems. In addition, further research is required, in the area of optimisation of energy modelling for Demand Shaping Measures, as well as for other energy sectors, notably transport, industry and agriculture. These are necessary to enable communities and cities to accurately design, plan ahead and implement the net zero and positive energy transition.

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A Appendix

A.1 Product Specifications

A.1.1 Solar Collector

Table A.1: Specifications of the Solar Collector, *source:*[\[42\]](#)

Manufacture Model		Pleion UNIKO P21
Dimensions (length x width x height)	<i>mm</i>	2018x1037x90
Gross surface area	<i>ml</i>	2,09
Aperture area	<i>ml</i>	1,82
Weight when empty	<i>kg</i>	35,1
Fluid content	<i>l</i>	1
Max test pressure	<i>bar</i>	10
Insulation rock wool	<i>mm</i>	40 + 20 LAT.
Transmittance coefficient <i>a1</i>	<i>W/m²K</i>	3,334
Transmittance coefficient <i>a2</i>	<i>W/m²K²</i>	0,02
Output no		80,8
Absorption coefficient	%	95
Emission coefficient	%	
Coefficient transfer of the glass	%	91,6
Thick glass	<i>mm</i>	3,2
Stagnation temperature	<i>°C</i>	204,9
Tilt minimum	<i>°</i>	15
Tilt maximum	<i>°</i>	75
Peak (max) power	<i>W</i>	1470
Recommended capacity	<i>K50°</i>	0,95

A.1.2 Photovoltaic module

Table A.2: Specifications of the Photovoltaic panel, *source:* [43]

Manufacture	Longi	
Model	LR4-72HBD-450M	
STC Power Rating	W	450
PTC Power Rating	W	422.2
STC Power per unit of area	W/m^2	207.0
Peak Efficiency	%	20.7
Power Tolerances	%	0/+5
Number of Cells		144
Imp	A	10.87
Vmp	V	41.4
Isc	A	11.58
Voc	V	49.6
NOCT	$^{\circ}C$	45
Maximum System Voltage	V	1500
80% Power Output Warranty Period	<i>yrs</i>	30
90% Power Output Warranty Period	<i>yrs</i>	12

A.1.3 Wind turbines

Table A.3: Wind turbines specs used in scenario 1, *source:* [44]

Manufacture	Gamesa	Gamesa	Vestas	Enercon
Rotor diameter	47 m	52 m	52 m	66 m
Swept area	1,735 m ²	2,124 m ²	2,124 m ²	3,412.2 m ²
Hub height	40/45/55 m	44 - 65 m	36.5 - 86 m	60 - 103 m
Rated power	660 kW	850 kW	850 kW	1500 kW
Cut-in wind speed	4 m/s	4m/s	4 m/s	3 m/s
Rated wind speed	15 m/s	13 m/s	14 m/s	12.5 m/s
Cut-out wind speed	25 m/s	25 m/s	25 m/s	25 m/s
Survival wind speed	59.5 m/s	-	60 m/s	70 m/s
Number of blades	3	3	3	3
Generator voltage	690 V	690 V	690 V	400 V
Generator grid connection	IGBT	Thyristor	asyncon	IGBT
Grid frequency	50 Hz	50/60 Hz	50 Hz	50 Hz

Table A.4: Wind turbines specs used in scenario 2, *source:* [44]

Manufacture	Siemens	Vestas	Vestas
Rotor diameter	62 m	90 m	90 m
Swept area	3,020 m ²	6,362 m ²	6,362 m ²
Hub height	68 - 90 m	80 - 105 m	80 - 105 m
Rated power	1300 kW	1800 kW	2000 kW
Cut-in wind speed	3 m/s	3.5 m/s	4 m/s
Rated wind speed	4 m/s	12 m/s	13 m/s
Cut-out wind speed	25 m/s	25 m/s	25 m/s
Survival wind speed	-	-	-
Number of blades	3	3	3
Generator voltage	690 V	690 V	690 V
Generator grid connection	ASYNCR	IGBT	OptiSpeed
Grid frequency	50 Hz	50/60 Hz	50 Hz

Table A.5: Wind turbines used in scenario 3, *source:* [44]

Manufacture	Vestas	Enercon	Siemens	Vestas
Rotor diameter	47 m	44 m	62 m	90 m
Swept area	1,735 m ²	1,521 m ²	3,020 m ²	6,362 m ²
Hub height	40 - 55 m	45/55 m	68 - 98 m	80 - 105 m
Rated power	660 kW	900 kW	1300 kW	2000 kW
Cut-in wind speed	4 m/s	3 m/s	3 m/s	4 m/s
Rated wind speed	15 m/s	16.5 m/s	14 m/s	13 m/s
Cut-out wind speed	25 m/s	34 m/s	25 m/s	25 m/s
Survival wind speed	59.5 m/s	59.5 m/s	-	-
Number of blades	3	3	3	3
Generator voltage	690 V	690 V	690 V	690 V
Generator grid connection	Thyristors	IGBT	-	OptiSpeed
Grid frequency	50 Hz	50 Hz	50 Hz	50 Hz

A.1.4 Battery

Table A.6: Battery specifications for scenario 1 and 2

Name	PerModAC
Nominal capacity	3.685 kWh
AC/DC coupling	AC
Technology	Li-ion
Charging efficiency	0.938
Discharging efficiency	0.938
Max. charging power	40000 W
Max.discharging power	40000 W
Full chaarging cycles	5000
Peripheral consumption	2 W
Stationary control deviation (charging)	41 W
Stationary control deviation (discharging)	- 32.6 W

A.2 Python Program

1. Computation and plots of the yearly production

```

1 import pandas as pd
2 import matplotlib.pyplot as plt
3 import seaborn as sns
4 import numpy as np
5 import time
6 import matplotlib.pyplot as plt
7
8 df=pd.read_csv("data/1.5MW.csv")
9
10
11 def get_mean_production() -> pd.DataFrame:
12     """Compute the mean production for each month and date.
13     """
14     # Read the data
15     # Extract month and day from the date column
16     df["date"] = pd.to_datetime(df["date"])
17     df["month"] = df["date"].dt.month
18     df["day"] = df["date"].dt.day
19
20     # Compute the mean for each month and hour

```

```
21     df_mean = df.groupby(["month", "day"]).mean(numeric_only=True
22     )
23     return df_mean
24 # Compute the mean production for each month and date
25 df_mean = get_mean_production()/1000
26 df_mean.columns=df_mean.columns.str.strip()
27 df_wind = df_mean["Wind Production [W]"]
28 df_solar = df_mean["Direct consumption from PV [W]"]
29 df_demand= df_mean["Demand of the community [W]"]
30 df_battery = df_mean["Battery discharge [W]"]
```

2. Collector heatmap code

```
1 import pandas as pd
2 import matplotlib.pyplot as plt
3 import seaborn as sns
4 import numpy as np
5
6 # Read the csv file
7 df=pd.read_csv("data/collector.csv",delimiter=",")
8 # Replace the comma with a dot in the Irradiation column
9 df['Irradiation'] = df['Irradiation'].str.replace(',', '.')
10 # Convert the Irradiation column to float type
11 df['Irradiation'] = df['Irradiation'].astype(float)
12
13 # Create a heatmap
14 heatmap_data = df.pivot_table(values='Irradiation', index='Hours',
15                               , columns='month')
16 sns.heatmap(heatmap_data, cmap='coolwarm')
17 # labels
18 plt.xlabel('Month of Year')
19 plt.ylabel('Hour of Day')
20 #invert y axis
21 plt.gca().invert_yaxis()
22 plt.show()
```

3. Direct consumption PV heatmap code

```
1 import pandas as pd
2 import matplotlib.pyplot as plt
3 import seaborn as sns
4 import numpy as np
5
6 df=pd.read_csv("data/1.5MW.csv")
7
8 # Create a heatmap
9 heatmap_data = df.pivot_table(values='Direct consumption from PV
    [W]', index='Hours', columns='month')/1000
10 sns.heatmap(heatmap_data, cmap='coolwarm', fmt='.1f', cbar_kws={'
    label': 'kW'})
11
12 plt.xlabel('Month of Year')
13 plt.ylabel('Hour of Day')
14 plt.gca().invert_yaxis()
15 plt.show()
```

4. Wind Production heatmap code

```
1 #Create a heatmap of the wind production
2 heatmap_data = df.pivot_table(values='Wind Production [W]', index
    ='Hours', columns='month')/1000
3 sns.heatmap(heatmap_data, cmap='coolwarm', fmt='.1f', cbar_kws={'
    label': 'kW'})
4 #plt.title('Hourly Energy Production (W) by Month of Year')
5 plt.xlabel('Month of Year')
6 plt.ylabel('Hour of Day')
7 plt.gca().invert_yaxis()
8 plt.show()
```

5. Demand heatmap code

```
1 # Create a heatmap of the demand
2 heatmap_data = df.pivot_table(values='Demand of the community [W]
    ', index='Hours', columns='month')/1000
```

```
3 sns.heatmap(heatmap_data, cmap='coolwarm', fmt='.1f', cbar_kws={'
    label': 'kW'})
4 #plt.title('Hourly Energy Production (kW) by month of Year')
5 plt.xlabel('Month of Year')
6 plt.ylabel('Hour of Day')
7 plt.gca().invert_yaxis()
8 plt.show()
```

6. Battery discharging heatmap code

```
1     # Create a heatmap of the battery discharging
2 heatmap_data = df.pivot_table(values='Battery Discharging [W]',
    index='Hours', columns='month')/1000
3 sns.heatmap(heatmap_data, cmap='coolwarm', fmt='.1f', cbar_kws={'
    label': 'kW'})
4 #plt.title('Hourly Energy Production (W) by month of Year')
5 plt.xlabel('Month of Year')
6 plt.ylabel('Hour of Day')
7 plt.gca().invert_yaxis()
8 plt.show()
```

A.3 Gantt Chart though-out the year

