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ΤΜΗΜΑ ΗΛΕΚΤΡΟΛΟΓΩΝ ΜΗΧΑΝΙΚΩΝ
& ΜΗΧΑΝΙΚΩΝ ΥΠΟΛΟΓΙΣΤΩΝ

Βέλτιστη επιλογή συστήματος Φ/Β μονάδας με υβριδική αποθήκευση για εξασφάλιση ενεργειακής αυτονομίας ξενοδοχειακής μονάδας

ΔΙΠΛΩΜΑΤΙΚΗ ΕΡΓΑΣΙΑ

ΣΤΕΛΛΑ ΜΠΟΖΗ

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ΑΥΤΗ Η ΣΕΛΙΔΑ ΕΙΝΑΙ ΣΚΟΠΙΜΑ ΛΕΥΚΗ

HELLENIC DEMOCRACY
UNIVERSITY OF WESTERN MACEDONIA
SCHOOL OF ENGINEERING
DEPARTMENT OF ELECTRICAL
& COMPUTER ENGINEERING

Optimal sizing of PV system coupled with hybrid storage to ensure the self-sufficiency of an off-grid hotel unit

THESIS

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November 2024
Kozani, Greece

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ΑΥΤΗ Η ΣΕΛΙΔΑ ΕΙΝΑΙ ΣΚΟΠΙΜΑ ΛΕΥΚΗ

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Δηλώνω ρητά ότι, σύμφωνα με το άρθρο 8 του Ν. 1599/1986 και τα άρθρα 2,4,6 παρ. 3 του Ν. 1256/1982, η παρούσα Διπλωματική Εργασία με τίτλο "Βέλτιστη επιλογή συστήματος Φ/Β μονάδας με υβριδική αποθήκευση για εξασφάλιση ενεργειακής αυτονομίας ξενοδοχειακής μονάδας. * Optimal sizing of PV system coupled with hybrid storage to ensure the self-sufficiency of an off-grid hotel unit." καθώς και τα ηλεκτρονικά αρχεία και πηγαίοι κώδικες που αναπτύχθηκαν ή τροποποιήθηκαν στα πλαίσια αυτής της εργασίας και αναφέρονται ρητώς μέσα στο κείμενο που συνοδεύουν, και η οποία έχει εκπονηθεί στο Τμήμα Ηλεκτρολόγων Μηχανικών και Μηχανικών Υπολογιστών του Πανεπιστημίου Δυτικής Μακεδονίας, υπό την επίβλεψη του μέλους του Τμήματος κ. Μπουχουρά Άγγελου αποτελεί αποκλειστικά προϊόν προσωπικής εργασίας και δεν προσβάλλει κάθε μορφής πνευματικά δικαιώματα τρίτων και δεν είναι προϊόν μερικής ή ολικής αντιγραφής, οι πηγές δε που χρησιμοποιήθηκαν περιορίζονται στις βιβλιογραφικές αναφορές και μόνον. Τα σημεία όπου έχω χρησιμοποιήσει ιδέες, κείμενο, αρχεία ή / και πηγές άλλων συγγραφέων, αναφέρονται ευδιάκριτα στο κείμενο με την κατάλληλη παραπομπή και η σχετική αναφορά περιλαμβάνεται στο τμήμα των βιβλιογραφικών αναφορών με πλήρη περιγραφή. Απαγορεύεται η αντιγραφή, αποθήκευση και διανομή της παρούσας εργασίας, εξ ολοκλήρου ή τμήματος αυτής, για εμπορικό σκοπό. Επιτρέπεται η ανατύπωση, αποθήκευση και διανομή για σκοπό μη κερδοσκοπικό, εκπαιδευτικής ή ερευνητικής φύσης, υπό την προϋπόθεση να αναφέρεται η πηγή προέλευσης και να διατηρείται το παρόν μήνυμα. Ερωτήματα που αφορούν τη χρήση της εργασίας για κερδοσκοπικό σκοπό πρέπει να απευθύνονται προς τον συγγραφέα. Οι απόψεις και τα συμπεράσματα που περιέχονται σε αυτό το έγγραφο εκφράζουν τον συγγραφέα και μόνο.

Υπογραφή Φοιτητή:

Στέλλα Μπόζη

ΑΥΤΗ Η ΣΕΛΙΔΑ ΕΙΝΑΙ ΣΚΟΠΙΜΑ ΛΕΥΚΗ

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Abstract (Greek): Περίληψη

Η παρούσα Διπλωματική Εργασία διερευνά την τεχνοοικονομική βιωσιμότητα ενός αυτόνομου μικροδικτύου μίας ξενοδοχειακής μονάδας 5 αστέρων σε ένα απομακρυσμένο νησί στην Βόρεια Ελλάδα, τροφοδοτούμενο εξ ολοκλήρου από Ανανεώσιμες Πηγές Ενέργειας (ΑΠΕ). Στόχο της μελέτης αποτελεί η διερεύνηση των χαρακτηριστικών ενός συστήματος που θα αξιοποιεί τις τεχνολογίες Συστήματος Φωτοβολταϊκών (PV), Αποθήκευσης Ενέργειας με Μπαταρίες (BESS) και Παραγωγής Υδρογόνου (P2H2P) ώστε να καλύπτονται πλήρως οι ενεργειακές ανάγκες μιας ξενοδοχειακής μονάδας 270 κλινών 5 αστέρων θερινής λειτουργίας. Στη Διπλωματική Εργασία εξετάζονται εναλλακτικές διατάξεις συστημάτων και αξιολογούνται ως προς την οικονομική τους απόδοση σε διάστημα 25 ετών.

Η μελέτη μοντελοποιεί τρία κύρια σενάρια, το κάθε ένα από τα οποία αντιπροσωπεύει έναν διαφορετικό συνδυασμό των στοιχείων PV, BESS και P2H2P. Το λογισμικό Hybrid Optimization of Multiple Energy Resources Pro (HOMER Pro) χρησιμοποιήθηκε για τον σχεδιασμό, την προσομοίωση και τη βελτιστοποίηση του αυτόνομου μικροδικτύου. Ένα τέταρτο σενάριο εξετάστηκε με σκοπό την διερεύνηση της οικονομικής βιωσιμότητας της σύνδεσης της απομακρυσμένης τοποθεσίας με το κεντρικό δίκτυο της χώρας, αντί της δημιουργίας ενός μικροδικτύου βασισμένου στην παραγωγή ενέργειας 100% από ΑΠΕ. Στόχος ήταν η εύρεση του ορίου του Αρχικού Κόστους Επένδυσης (CAPEX) της διασύνδεσης στο οποίο γίνεται οικονομικά αποδεκτό να αναπτυχθεί ένα αυτόνομο μικροδίκτυο με χρήση ΑΠΕ.

Στις προσομοιώσεις χρησιμοποιήθηκαν ωριαία δεδομένα καταναλώσεων ηλεκτρικής ενέργειας από υπάρχουσες και εν λειτουργία ξενοδοχειακές μονάδες. Για τη συγκεκριμένη ξενοδοχειακή μονάδα η ετήσια κατανάλωση AC ανήλθε στις 1354.677 MWh, με μέση ημερήσια κατανάλωση στις 3715 kWh και μέγιστο φορτίο 403.87 kW. Οι εποχιακές διακυμάνσεις της ζήτησης ενέργειας ήταν κρίσιμος παράγοντας στον σχεδιασμό του συστήματος.

Τα αποτελέσματα παρουσιάζουν ότι ο συνδυασμός PV - BESS μπορεί να καλύψει αξιόπιστα τις ενεργειακές ανάγκες της ξενοδοχειακής μονάδας καθ' όλη τη διάρκεια του έτους με το μικρότερο NPC συγκριτικά με τα υπόλοιπα σενάρια 100% παραγωγής ηλεκτρικής ενέργειας από ΑΠΕ. Το σενάριο που ενσωματώνει PV, BESS και P2H2P έχει το δεύτερο χαμηλότερο NPC με διαφορά 0.127 €/kWh στο Κανονικοποιημένο Κόστος Ενέργειας (LCOE) σε σύγκριση με την καλύτερη επιλογή. Το τέταρτο σενάριο ανέδειξε την οικονομική βιωσιμότητα του αυτόνομου μικροδικτύου αν το CAPEX για τη διασύνδεση του έργου με το δίκτυο υπερβεί τα 9.7 εκατομμύρια ευρώ, ένα ποσό που δεν είναι απίθανο να ζητηθεί.

Αυτή η Διπλωματική Εργασία καλύπτει ένα σημαντικό κενό στην υπάρχουσα βιβλιογραφία, προσφέροντας μία λεπτομερή ανάλυση ενός αυτόνομου μικροδικτύου με παραγόμενη ηλεκτρική ενέργεια εξ 'ολοκλήρου από ΑΠΕ για μία ξενοδοχειακή μονάδα με έντονα μεταβαλλόμενη εποχιακή ζήτηση του φορτίου. Συνολικά, η έρευνα προσφέρει πολύτιμες πληροφορίες σχετικά με τον σχεδιασμό ενός αυτόνομου μικροδικτύου πλήρως τροφοδοτούμενο από ΑΠΕ για εμπορικές εφαρμογές σε απομονωμένες περιοχές, ανοίγοντας τον δρόμο για πιο βιώσιμες ενεργειακές λύσεις σε παρόμοιες απομακρυσμένες τοποθεσίες.

Key words (Greek): Λέξεις κλειδιά

Ανανεώσιμες Πηγές Ενέργειας (ΑΠΕ), Αυτόνομο Μικροδίκτυο, Μικροδίκτυο Φ/Β – Σύστηματος Αποθήκευσης Ενέργειας με Μπαταρίες, Σύστημα Παραγωγής Υδρογόνου (Power to Hydrogen to Power - P2H2P), Τεχνοοικονομική ανάλυση, HOMER Pro λογισμικό βελτιστοποίησης

Abstract

This thesis investigates the techno-economic feasibility of a stand-alone microgrid system powered entirely by renewable energy sources, designed for a 5 – star, 270 beds resort on a remote island in northern Greece. The key challenge is to meet the resort's energy needs sustainably and reliably, without using any conventional diesel generators. Having created the resort's unique energy consumption patterns, marked by seasonal demand peaks in the summer and low consumption in the winter, the primary objective of the study is to develop an optimal sustainable energy system using Photovoltaic panels (PV), a Battery Energy Storage System (BESS), and a Power to Hydrogen to Power (P2H2P) system. The study explores different configurations of the above systems over a 25-year project lifetime, focusing on minimizing the total Net Present Cost (NPC) of the project.

The study models three main scenarios, each representing a different combination of PV, BESS and P2H2P systems. Hybrid Optimization of Multiple Energy Resources Pro (HOMER Pro) software is used to design, simulate, and optimize the stand-alone microgrid. The software optimizes the sizing of the components by searching for the lowest NPC for each configuration. A fourth scenario is conducted to investigate the financial viability of connecting the remote location to the main grid rather than forming a 100% RE system. Various initial interconnection investment costs are considered to determine the threshold at which it becomes more cost-effective to develop a self-sustained microgrid using renewable energy sources instead of relying on grid connection.

The simulations used hourly energy consumption data from existing and already operating resorts. The dataset indicated an AC annual load of 1,354.677 MWh with average daily load of 3,715 kWh and peak load of 403.87 kW, providing a realistic representation of the resort's annual demand, enabling accurate modeling of its energy generation and storage needs. Seasonal fluctuations of energy demand were a critical factor in the system design.

The results indicate that the combination of PV and a BESS can reliably meet the resort's energy needs throughout the year, even during peak summer months, while also providing the lowest NPC among all three 100% renewable energy (RE) scenarios. The scenario incorporating PV, BESS, P2H2P system resulted in the second-lowest NPC, with a Levelized Cost of Energy (LCOE) difference of 0.127 €/kWh compared to the best option. The fourth scenario revealed that the stand-alone microgrid is the only financially feasible option if the CAPEX for connecting the remote resort to the grid exceeds 9.7 million euros, which is not an unlikely figure.

In conclusion, this thesis fills a critical gap in the existing literature by offering a detailed analysis of a 100% RE stand-alone microgrid of a resort with highly variable seasonal load demand. Overall, the research contributes valuable insights into the design of fully RE systems for commercial applications in isolated areas, paving the way for more sustainable energy solutions in similar remote settings.

Keywords

Renewable Energy (RE), Stand-alone microgrid (SAM), PV – BESS microgrid, Power to Hydrogen to Power system (P2H2P), Techno-economic analysis, HOMER Pro optimization software

List of Abbreviations

Abbreviation	Definition
BESS	Battery Energy Storage System
CAPEX	Capital Expenditures
COE	Cost of Energy
DG	Diesel Generator
DoD	Depth of Discharge
FC	Fuel Cell
HOMER Pro	Hybrid Optimization of Multiple Energy Resources Pro
HRES	Hybrid Renewable Energy Systems
LCOE	Levelized Cost of Energy
NPC	Net Present Cost
OPEX	Operating Expenses
P2H2P	Power to Hydrogen to Power system
PV	Photovoltaic system
RE	Renewable Energy
RES	Renewable Energy Sources
SAM	Stand - Alone Microgrid

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Chapter 1: Introduction

1.1 Motivation

The buildings and construction sector is the leading source of greenhouse gas emissions, responsible for an overwhelming 37% of global emissions [6]. Resorts account for approximately 1% of global carbon dioxide emissions. In 2021, out of the 36.3 billion tons of carbon dioxide released worldwide, resorts were responsible for around 363 million tons, an amount roughly equivalent to the annual emissions of 45.7 million homes.
Scientists have determined that a global temperature rise of up to 2°C above the pre-industrial average is the acceptable limit by 2050. Achieving this goal requires significant reductions in carbon dioxide emissions across all sectors, with a particular emphasis on the buildings sector due to its substantial contribution to global emissions.

Most off-grid systems have traditionally relied on diesel generators to ensure autonomy, often coupled with Renewable Energy (RE) technologies, with or without a Battery Energy Storage System (BESS). Even though this approach has been effective, it has led to significant emissions. Current RE technologies, such as solar, wind or hydroelectric, often face challenges on maintaining a stable energy generation due to their dependence on weather conditions, which may change multiple times per day. Therefore, a storage system is essential to ensure that during the time periods of high energy production, the excess energy will be stored to be used later, when the conditions do not allow to generate the energy that is required to meet the load. BESS and pumped hydro storage are commonly used in energy storage systems, however they come with technical and financial limitations.

Designing a SAM in a remote/ islanded area for a 5-star resort poses significant challenges, due to the resort's high energy demand which must be met at all costs to ensure visitors' satisfaction. A decentralized system like this requires local electricity generation sources to meet the localized energy needs, as well as a storage system to ensure the system's reliability.
The primary challenge of this thesis lies in designing this islanded SAM while selecting and sizing the optimal technologies and balancing system reliability with minimizing both capital and operational costs.

1.2 Purpose of the Thesis

The purpose of this thesis is to develop and analyze different scenarios of power generation and storage for a SAM to meet the energy needs of a 5-star, 270 beds resort. Currently, research has been conducted in the field of microgrids, exploring various scenarios to evaluate the technological and financial feasibility of establishing a microgrid in a remote area. The existing bibliography primarily focuses on specific types of loads, usually annual loads with low demand, such as those of small offices, households, or small communities. This research seeks to introduce a solution that optimizes the sizing of components of a 100% RE with the goal of minimizing the total Net Present Cost (NPC) of the project in an islanded area in northern Greece. The study evaluates a potential seasonal load from a 5-star resort to ensure the reliability of the microgrid.

The findings of this thesis are expected to contribute to the advancement of stand-alone microgrids by providing technical and financial data that could improve the autonomy of a seasonal and high load demand in a remote area. Through extensive simulations in HOMER Pro software, this study will provide practical and financial insights into the most effective method for similar cases to the one analyzed in this thesis.

1.3 Hypothesis

The core issue in this research is determining the optimal sizing of components for a 100% RE system to minimize NPC and ensure reliability for a 5-star, 270 beds seasonal resort in a remote islanded area in northern Greece. The study will evaluate three 100% RE scenarios, including solar PV system, BESS and P2H2P system. The results of these simulations will be analyzed and compared to the NPC and LCOE for the same system if connected to the grid. This leads to the hypothesis following hypothesis:

Hypothesis 1: By optimizing the sizing of microgrid's components, it is possible that a stand-alone 100% RE microgrid could be a techno-economic feasible solution for the project.

Hypothesis 2: Scenarios with P2H2P systems will have higher NPC than the scenario that does not include these components but will ensure a more reliable system.

The key variables involved in testing this hypothesis include the size and configuration of RE and P2H2P components, as well as financial parameters such as the NPC, LCOE, OPEX and CAPEX.

1.4 Literature review

This study's research is divided into the three following sectors into which the related work from other studies can be categorized: stand-alone system, Hybrid Renewable Energy Systems (HRES) and resort. With advancements in the technologies utilized by P2H2P systems, these systems have now been a reliable source of seasonal storage and production in isolated areas. Not only do they enhance the reliability of an off-grid system but also offer an alternative to avoid grid connection, thereby improving grid reliability and alleviating congestion.

Beginning with the oldest papers to the most recent ones, this chapter is focused on reviewing the existing literature.

E. I. Zoulias at al. [7] performed a techno-economic analysis on the integration of P2H2P technologies (electrolyzers, fuel cells, and hydrogen storage tanks) into a RE stand-alone system in Kythnos Island, Greece. HOMER software was used to simulate the system (PV-P2H2P) and compare it to the existing PV-diesel setup. The study proved that it is technically feasible to replace fossil fuel-based generators with hydrogen technologies. G. J. Dalton at al. [8] analyzed a SAM of a resort with over 100 beds. The average energy consumption of the resort was 15000 kWh/day, with a peak load of 966 kW. It was concluded that a hybrid diesel/RE configuration would provide the lowest NPC.

L. H. Jing Li at al. [9] analyzed the optimal configuration of a large residential community with a daily average power consumption about 28,634 kWh and peak load 6,169 kW in residential community in Beijing, China. The area allowed the installation of both PV and wind turbines. The results of the simulations in HOMER Pro indicate that the microgrid could supply successfully 90% of the onsite electricity demand with 47–100% RE sources. It is also shown that it is more cost-efficient when wind power becomes the main energy source, while combined with PV. Finally, the scenarios that were simulated without a BESS proved to be less cost-effective than those that a BESS was included.

H. Zahboune at al. [10] explore the MESCA method for optimizing a standalone hybrid PV/wind power system with battery storage, applying it to a residential area in Oujda, Marocco, with a primary load of 18.7 kWh/ day. The optimal design resulted in a LCOE of 0.374 €/kWh. V. Suresh at al. [11] conducted a study on the modelling and optimization of an off-grid hybrid energy system for three village hamlets in Kollegal block, Karnataka, India, assessing four combinations of HRES. The total energy demand in the area was estimated at 724.83 kWh/day, with a peak load of 149.21 kW. The four combinations included various setups of solar PV, wind turbines, biomass gasifiers, fuel cells and BESS. The configuration that included all components was found to have the lowest NPC and LCOE of 0.15 €/kWh.

The latest studies prove that isolated remote communities with medium load a P2H2P system is often chosen coupled with PV and BESS. F. Dawood at al. [12] analyzed a 100% renewable energy SAM in a hypothetical remote community in the Western part of Australia. The community consisted of 100 households and a few small commercial buildings and factories. The semi-residential daily load profile was 2 MWh

AC and 192 kW peak. The researchers evaluated the techno-economic feasibility of a RE system using hydrogen as energy storage for a SAM. HOMER Pro software was used to simulate the system, while the results showed that the hydrogen-battery hybrid energy storage system is the most cost-effective scenario and has significant potential in electrifying remote communities. G. Lacey at al. [13] investigated the techno-economic feasibility of including RE to support the operation of a hotel unit on Myanmar's west coast with a capability of grid connection limited to 5 hours per day. The study's results showed that it was not economically realistic to build a microgrid which supplies 100% of the load, so a hybrid diesel generator and PV array were chosen to cover a demand of 20%.

M. G. Basiony at al. [14] developed a mathematical system model, implemented using MATLAB/Simulink, to analyze the performance and sizing of different components in a standalone microgrid. The system included PV panels, an electrolyzer, fuel cells, hydrogen storage and a multi-effect mechanical vapor compression (MED-MVC) desalination unit. The study focused on meeting both the freshwater production and the annual energy demand of 255.17 MWh for a building in New Bord El-Arab City, Egypt. Simulation results demonstrated a viable solution capable of fulfilling the energy and freshwater needs, with a LCOE of 0.64 €/kWh.

1.5 Contribution

There is extensive research on techno-economic feasibility of stand-alone microgrids in small, medium, and larger communities using PV-BESS or P2H2P systems. However, upon reviewing the available studies, it became evident that there is no updated research available on SAM of resorts in remote areas. Resorts differ significantly from residential communities or offices in terms of the daily energy demand patterns, peak load timing, and annual load distribution. This is particularly true in seasonal resorts, where the energy demand is very low during the winter months but peaks dramatically during summer, highlighting the need for seasonal energy storage. In addition, most of the available research focuses on comparing a traditional diesel generator set up with PV-BESS or P2H2P systems.

This study is addressing these gaps by focusing on a resort with seasonal operation on a remote island in northern Greece, by creating a SAM with 100% RE with no DG. Different scenarios are explored to conduct a techno-economic analysis and identify the optimal configuration with the lowest NPC. Due to the location and the nature of the project, certain restrictions are considered in the analysis.

1.6 Organization

In this study the following organization system is used to ensure the gentle introduction of the reader to the case study.

In Chapter 2, the theoretical background needed for the study is analyzed. The methodology used in this study is described in Chapter 3, including the software, data analysis and mathematical analysis of the problem and its components. Chapter 4 is dedicated to introducing the case study to the reader, explaining the different scenarios of the problem, and detailing the input data. The results for each scenario and outputs of the simulations in HOMER Pro can be found in Chapter 5, while also including a sensitivity analysis. In Chapter 6, the study's conclusions are analyzed, and suggestions for future work are presented. Following this, supporting documents and files used throughout the thesis are detailed, concluding with the bibliography.

Chapter 2: Theoretical background

2.1 Introduction

In this chapter the theoretical background of the study is analyzed. The main key words of the research as well as other terms used in the study are explained.

2.2 Small Power Systems (SPSs)

Small Power Systems (SPS) is an electrical power system designed to generate and distribute electricity in small-scale applications. These types of systems are often used in remote areas, microgrids or residential setups where large scale grids are not technically or financially feasible. Depending on the connections to the grid, SPS can be grid-connected or off-grid.
As for their scale, SPS often serve smaller geographic areas, and a limited number of consumers compared to larger power grids. The system could generate energy from various types of sources, for example RES (solar, wind), DG, or a combination of the above to ensure reliability (hybrid SPS) [1].

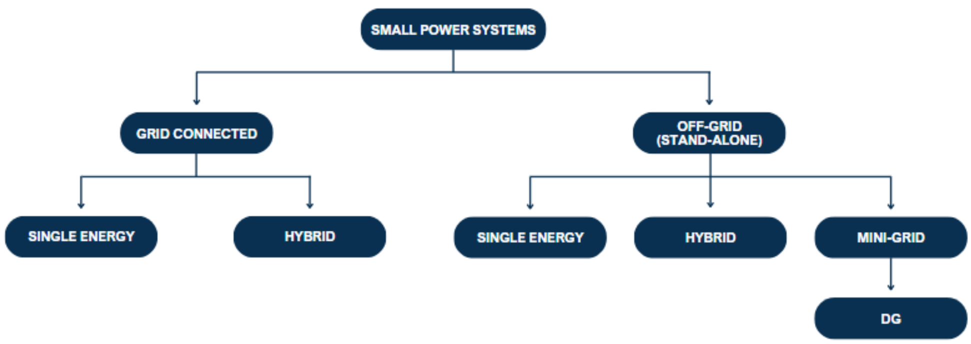

Figure 2.1: Small Power Systems, Source: [1]

2.2.1 Grid Connected systems (GC)

Grid connected (GC) systems are larger independent decentralized setups that can operate when connection to the main electricity transmission and distribution system has been made. The capacity of these types of systems is determined but the supply source and the systems operates only if there is available supply sources [15].

2.2.2 Stand-Alone Microgrids (SAM)

Stand-alone microgrids (SAM) are suitable for remote locations, in areas where grid connection is not the technically or financially a feasible choice. The operational capacity of the system is matched to its demand. To ensure its reliability a storage unit, such as BESS or P2H2P system needs to be implemented.

2.3 Photovoltaic system (PV)

A Photovoltaic (PV) system is a RE power generation system designed to convert solar radiation into electrical energy. The main part of this technology is the solar cell modules. Their applications vary from small residential setups (GC or SAM) to large scale solar farms. SPV electrical direct current (DC) power production systems show many advantages such as the absence of CO2 emissions and the lack expenses regarding fuel costs [16].

2.4 BESS

A Battery Energy Storage System (BESS) is a supporting system with a rapid response time, high reliability, and low self-discharge rate. Depending on the application in which is going to be used, there are specific attributes, such as the name, capacity, energy, power output, charging/discharging rates, efficiency, life cycle, and cost, that must be taken into consideration to determine the most efficient BESS for the system.

A very common battery energy technology is lithium-ion batteries. Their main advantages are portability, high energy density, and fast response time. However, the downsides of this type of technology is its high cost and limited capacity [17]. Therefore, their use is primarily for hourly and daily storage, which highlights the need to find methods for seasonal energy storage.

2.5 Power to Hydrogen to Power (P2H2P) Systems

2.5.1 Introduction

Power-to-hydrogen-to-power (P2H2P) is an upcoming alternative of BESS to overcome their technical and financial challenges. According to B. Modu at al. [18] hydrogen (H_2) is considered a form of renewable energy storage due to its ability to be produced through the process of electrolysis and stored in tanks.

As shown in Figure 2.2, P2H2P systems convert excess electricity to gaseous hydrogen via electrolysis which is later stored in gas tanks or transferred through pipelines [2]. A fuel cell (FC) converts stored hydrogen into electricity during time periods when the generated energy from the RES does not match the load.
Due to the increased fuel prices, P2H2P is considered a financially viable solution in mini-grid systems with zero CO2 emissions [19].

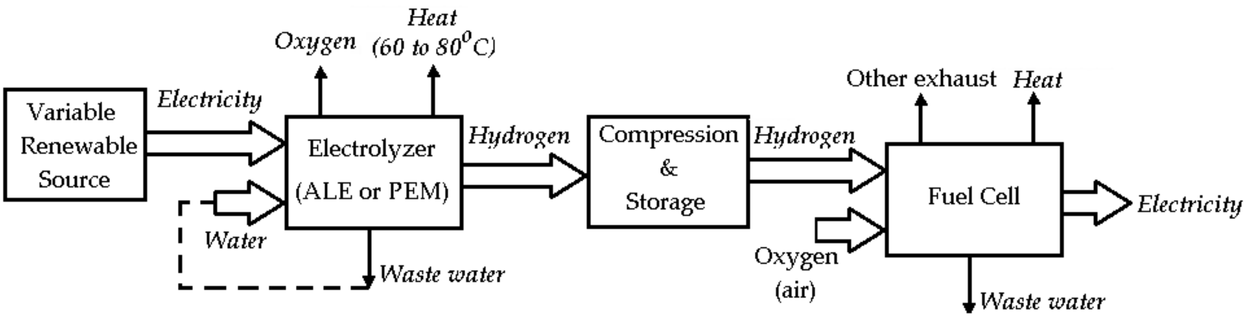

Figure 2.2: P2H2P systems, Source: [2]

As shown in Figure 2.2, the considered elements in a P2H2P system are the electrolyzer, hydrogen tank and fuel cell. All these technologies are presented in this chapter.

2.5.2 Electrolysis & Electrolyzer

Electrolysis refers to the process which splits water into hydrogen and oxygen by applying DC current within an electrolyzer [20]. Green (renewable) hydrogen is produced by RES via the process of electrolysis.

The electrolysis process is represented by the reaction in Equation 2.1.

$$H_2O \rightarrow 2H_2 + O_2 \qquad \Delta H^o = 286\ kJ/mole\ (at\ 25^oC, 1\ bar) \qquad (2.1)$$

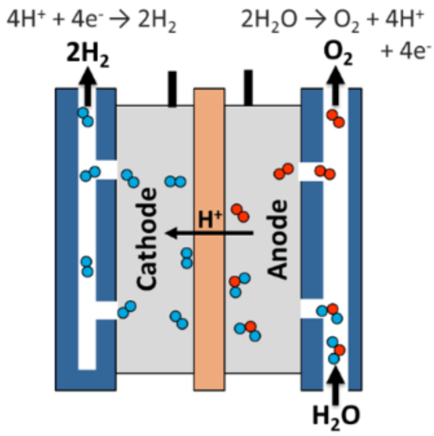

Figure 2.3: Electrolysis process, Source: [3]

There are three main water electrolysis technologies that are mostly mentioned in literature [21]:

- Alkaline water electrolysis (AWE)
- Proton exchange membrane (PEM)
- Solid oxide electrolyte (SOE).

As shown in Figure 2.3 the inputs of an electrolyzer are the electric energy from RES and water, while the main output is hydrogen. Secondary outputs are considered the oxygen and heat.

2.5.3 Hydrogen Storage

The main product of electrolysis, the H_2, requires compression to enhance its volumetric energy density and allow it to transfer it or utilize it as a source for electric power generation [2]. Once the hydrogen has been compressed, it is stored at a pressure not exceeding 200 bar [14].

Figure 2.4: Hydrogen Storage, Source: [4]

Hydrogen storage is necessary for a stand-alone energy system to always ensure that the load demand will be met, even when energy produced by RES is insufficient.

2.5.4 Fuel Cell (FC)

A lot of attention has been drawn to hydrogen fuel cell technology, due to its high efficiency, low levels of noise and pollution compared to other chemical energy conversion, such as DG.

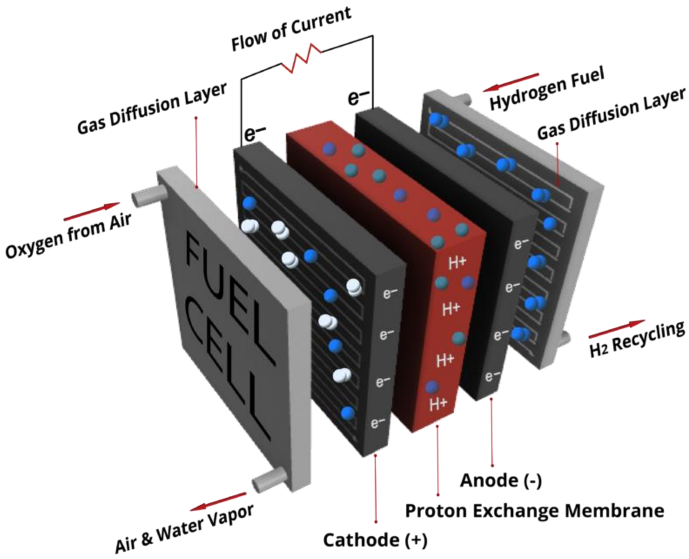

Figure 2.5: A typical Fuel Cell, Source: [5]

Fuel cells essentially operate as the reverse process of electrolysis. A fuel cell is an electrochemical device that generates power through oxidation/reduction reactions. As shown in Figure 2.5 it consists of an electrolyte membrane placed in between two catalyst-coated electrodes, the anode and the cathode. Oxygen drawn from the air flows through one electrode while at the same time hydrogen flows through the other. This reaction generates energy, along with water and heat as byproducts [22].

The proton exchange membrane fuel cell (PEMFC) is one of the best forms of fuel cell for distributed power production systems, since it runs at lower temperatures and can start and stop faster than other types of fuel cells [18].

2.6 Hybrid Renewable Energy System (HRES)

A Hybrid Renewable Energy System (HRES) combines RES (solar, wind, hydroelectric power) with on-site H_2 production and storage [23]. Adding FC to a RES system can reduce the size of the BESS, extend project's lifetime, and enhance overall system performance [18]. This type of system can be implemented in both grid-connected or stand-alone systems.
In large-scale energy systems, hydrogen can be used for ancillary purposes to stabilize the grid by absorbing excess renewable energy and releasing it back to the grid when necessary. In off-grid locations, RES-H_2 hybrid can be implemented to provide a self-sufficient energy solution.

2.7 Dispatch Strategies

Load Following (LF) and Cycle Charging (CC) are the two dispatch strategies used in hybrid power systems, crucial for managing energy production while optimizing efficiency.

2.7.1 Load Following (LF)

In the Load Following (LF) strategy, when RES are available the system uses it to meet the load. If the demand is not satisfied with the RES production, a generator produces only enough power to meet the remaining demand. Charging the storage bank is only charged by the RES. This strategy is particularly effective in a system where RES is the main source of power production.

2.7.2 Cycle Charging (CC)

In the Cycle charging (CC) strategy, the generator is running at full capacity if turned on despite the load. When there is excess energy produced by the generator, the storage system is charged, and once it is fully charged, the generator shuts down. The system then relies on the storage system until it is fully discharged and the process repeats. Cycle charging strategy tends to be optimal in little or no renewable power systems.

2.8 Financial Terminology

This study incorporates many economic terms, with the four key terms that shape the thesis outcomes described below.

2.8.1 Net Present Cost (NPC)

Net Present Cost (NPC) is a financial metric that is used to calculate the total cost of a project or investment over its lifetime, expressed in present-day economic value. It consists of both the initial capital investment and any future costs, such as operation & maintenance or replacement. By discounting future costs to their present value, NPC provides a comprehensive view of the total cost of the project, allowing comparisons between different investment options.

2.8.2 Capital Expenditure (CAPEX)

Capital Expenditure (CAPEX) refers to the funds needed to be invested in a project to provide value over an extended period. In this study, when the term CAPEX is used, it specifically refers to the initial CAPEX of the project.

2.8.3 Operation & Maintenance Expenditures (OPEX)

Operation & Maintenance Expenditures (OPEX) refer to the ongoing costs required for the daily functioning of the project. Unlike CAPEX, which involves one-time large investments, OPEX covers recurring expenses that are necessary for maintaining regular operations.

2.8.4 Levelized Cost of Energy (LCOE)

Levelized Coste of Energy (LCOE) is a metric used to calculate the average cost of energy generation over the lifetime of the project. It considers all the costs associated with the project, including CAPEX, OPEX and emissions penalties LCOE is expressed in €/kWh.
This term helps to compare different energy technologies by averaging costs over the system's lifecycle, making it easier to determine which energy production system is the most economically feasible.

Chapter 3: Methodology

3.1 Introduction

This chapter presents the software used for the simulations of this research, as well as the mathematical modelling of the components and mathematical analysis of the system. HOMER Pro was used for the simulation of the research to optimize components' sizing to achieve the lowest Net Present Cost (NPC). The software uses several mathematical formulas during the optimization process which are all explained in this chapter.

3.2 Software: HOMER Pro

The Hybrid Optimization of Multiple Energy Resources Pro (HOMER Pro) is a software developed by the National Renewable Energy Laboratory (NREL - USA), and is widely used to design, simulate and optimize microgrids. Through HOMER Pro the researcher can compare different power technology components, getting information about their physical behavior, purchase, installation and operation costs. It allows users to simulate both grid-connected and off-grid systems with various energy sources available, such as solar PV, wind turbines, DG, and storage systems like BESS or P2H2P. During the simulation process, it performs chronological simulations to evaluate system performance over the years, optimizing the Net Present Cost (NPC) by considering fuel prices, weather conditions and consumption. It evaluates different combinations of the above components to propose the most optimal combination of technologies that minimizes the total NPC.

HOMER Pro requires input data regarding the location of the microgrid, weather data and electrical load that needs to be served. If needed to be used, a specific BESS is required to be chosen from a wide range of battery components. The software optimizes the parallel strings for the BESS. Generators can be either chosen from the suggested list or create a custom one.

3.3 Modelling of system components

Modelling of the RES-H_2 system is a crucial step to understand the algorithm HOMER Pro software uses to optimize the sizing of the components in each simulation. The mathematical modelling for the components used in the scenarios is explained below.

3.3.1 Solar PV system & Inverter

Equation 3.1 calculates the output of the PV array.

$$P_{PV} = Y_{PV} f_{PV} \left(\frac{\overline{G_T}}{\overline{G_{T,STC}}}\right) \left[1 + a_P\left(T_C - T_{C,STC}\right)\right] \quad (3.1)$$

Where Y_{PV} stands for the rated capacity (kW) of the PV array, meaning its power output in standard conditions, f_{PV} is the PV derating factor (%), $\overline{G_T}$ stands for the solar radiation incident on the PV array in the current time step (kW/m^2), while $\overline{G_{T,STC}}$ deals with the incident radiation at standard test conditions (1 kW/m^2). The a_P is the temperature coefficient of power (%/°C), the T_C and $T_{C,STC}$ is the PV cell temperature in the current time step (°C) and under standard test conditions (25°C) respectively.

HOMER Pro allows the user to enter the cost, performance characteristics, and orientation of an array of photovoltaic (PV) panels and choose its size. The user can either allow the software to optimize the PV size based on the needs, or manually select the size of the PV system. The selection of the inverter and its characteristics can be made using the same process and information as described above for the PV system.

3.3.2 BESS

As for the battery bank, the software offers a selection of battery banks that the user can choose from a library. The user can review the technical details and specify the costs. All this information is drawn from datasheets of BESS manufacturers. Apart from the finances of the battery bank, the user is also able to adjust the State of Charge (SoC) to the desirable value. HOMER Pro is capable of sizing and optimizing the strings used in the BESS.

Then availability of power in the battery bank at any time is described by A. Chauhan at al. [24] in Equation 3.2.

$$E_{Batt}(t) = E_{Batt}(t-1) + E_{EE}(t) * \eta_{CC} * \eta_{CHG} \quad (3.2)$$

where, $E_{EE}(t)$ is the extra energy available from all the systems, η_{CC} is the charging controller efficiency, and η_{CHG} the battery charging efficiency.

3.3.3. Electrolyzer

In HOMER Pro, the user can specify electrolyzer's costs, efficiency, while the software can optimize electrolyzer's size in term of maximum electrical output.

The power transferred from electrolyzer to hydrogen storage tank is described by V. Suresh at al. [11] Equation 3.3.

$$P_{Elec-Tank} = P_{Ren-Elec} * \eta_{Elec} \tag{3.3}$$

where, η_{Elec} is the electrolyzer efficiency assumed as constant.

3.3.4 Hydrogen tank

HOMER Pro assumes that adding H_2 to the tank does not require electricity and that the tank does not experience any leakage. The user can specify tank's finances, efficiency, while the software is capable on optimizing tank's capacity (kg).

The mass of hydrogen storage is calculated using the Equation 3.4.

$$m_{Tank}(t) = \frac{E_{Tank}(t)}{HHV_{H2}} \tag{3.4}$$

where, HHV_{H2} is hydrogen storage higher-heating value considered as 38.9 kWh/kg [11].

3.3.5 Fuel Cell

In HOMER Pro, the user can specify the size of the fuel cell in terms of maximum electrical output and the components finances.

The output power of a Fuel Cell is described by M. J. Khan at al. [25] in Equation 3.5.

$$P_{FC} = P_{TANK-FC} * \eta_{FC} \tag{3.5}$$

3.4 Mathematical analysis of the problem

HOMER Pro targets on minimizing the Net Present Cost (NPC) when optimizing the system's components. The NPC of a system is the present value of all the costs the system incurs over its lifetime subtracting the present value of all the revenue it earns over its lifetime. It includes variety of costs including the capital costs, replacement, Operation & Maintenance (O&M), fuel, buying power from the grid, penalties and emissions. Revenues include income from selling power to the grid, when available. In remote, stand-alone systems, the revenue value is set to zero, due to the lack of connection with the grid [26].

HOMER Pro uses Equation 3.6 to calculate the Total Net Present Cost (TNPC):

$$TNPC = CC + O\&MC + RC + FC \tag{3.6}$$

where, CC is the total capital cost, $O\&MC$ is the total maintenance & operation, RC stands for the cost of replacement and FC is the cost of fuel and all the system components. As mentioned above, in this study the revenue value is set to zero due to the stand-alone system that is analyzed.

For hybrid RE systems, the cost of energy (COE) is calculated by using Equation 3.7:

$$COE = TNPC * \frac{CRF}{E_{prim}+E_{def}+E_{grid,sales}} \tag{3.7}$$

where $E_{prim}$is the primary load, E_{def} the deferrable load, $E_{grid,sales}$ the amount of electrical energy sold to the grid each year and CRF the Capital Recovery Factor and is calculated by Equation 3.8.

$$CRF = \frac{\gamma(1+\gamma)^{\tau}}{\gamma(1+\gamma)^{\tau}-1} \tag{3.8}$$

where γ the rate of annual interest and τ the plant life [11].

Chapter 4: Case study

4.1 Weather Data

The case study analyzes the stand-alone microgrid of a potential resort on a remote island in northern Greece.
HOMER Pro software allows the user to enter the exact location of the study area, and uses solar data downloaded from NASA Prediction of Worldwide Energy Resources for the exact latitude and longitude of the location entered. As shown in Figure 4.1, the scaled average annual global horizontal solar irradiation is 4.15 kWh/m²/day. The clearness index, which indicates the rate of solar irradiation passing through the atmosphere and reaching earth's surfy surface, tends to be high on clear, sunny days and low during cloudy conditions.

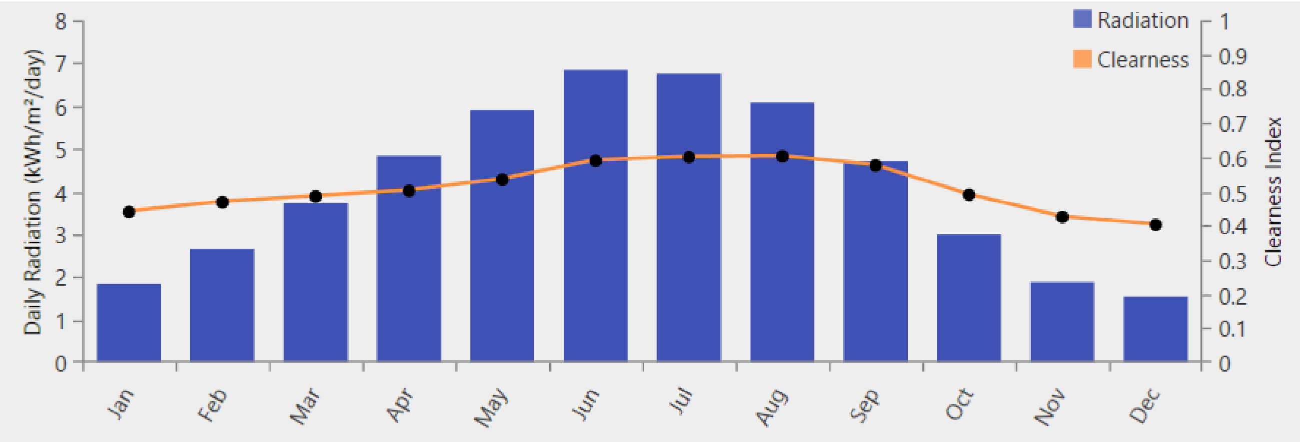

Figure 4.1: Daily Radiation & Clearness Index of Case Study location

Figure 4.3 shows the temperature data for the case study location downloaded from the NASA Surface Meteorology and Solar Energy database. This information is used for the operation of the PV system, which is negatively affected when the temperature of the environment is high. The annual average temperature is 16.24°C, but during the summer months, it can reach 27°C.

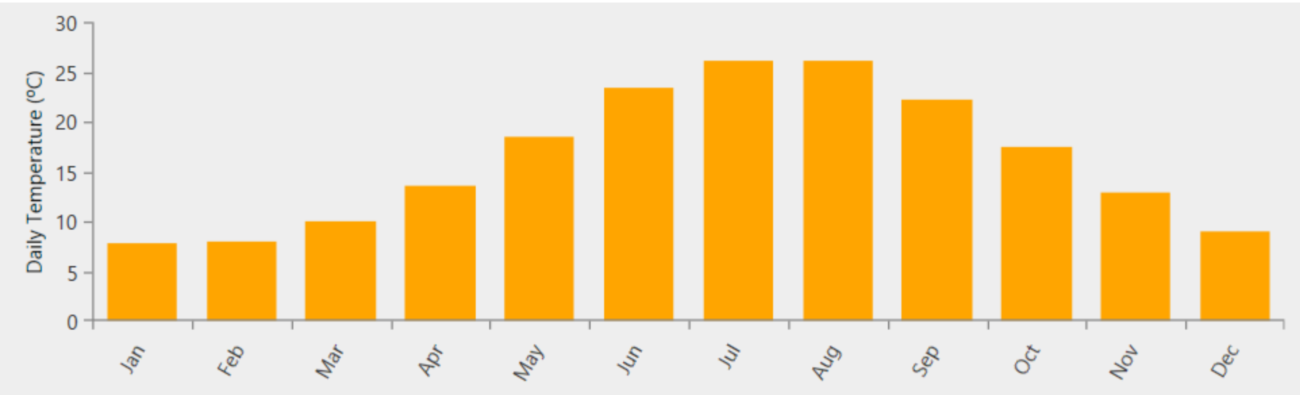

Figure 4.2: Daily Temperatures of Case Study location

4.2 Data processing

The resort, with a maximum capacity of 270 guests, will be operating seasonally from March 31st to October 26th. To simulate the SAM, hourly electricity load demand data for the entire year was required.
Load data from a resort with a capacity of 1,200 guests were successfully collected. Although this resort is located on Kos Island, Greece, it shares ownership with the case-study resort and has similar characteristics. Both are luxury, all-inclusive, 5-star resorts, offering the same pool surface area per guest, and employing identical techniques for heating, cooling, water processing and automation systems. An analysis of the data collected from all the company's resorts revealed that daily electricity demand is not significantly impacted by the varying regions of Greece, despite the potential differences in climate zones. The electricity demand was estimated to fall between 24 and 28 kWh per guest per night. Additionally, all resorts exhibited a similar guest capacity profile throughout the year.

The electricity demand load dataset, with 1-hour resolution, for the resort in Kos Island covered the period from July 12th to December 31st, 2023. This created the need to generate data for the remaining of the year (January 1st to July 11th). Additionally, a document outlining the resort's daily energy consumption throughout the year was provided.

Figure 4.3 displays the data drawn from the existing resort.

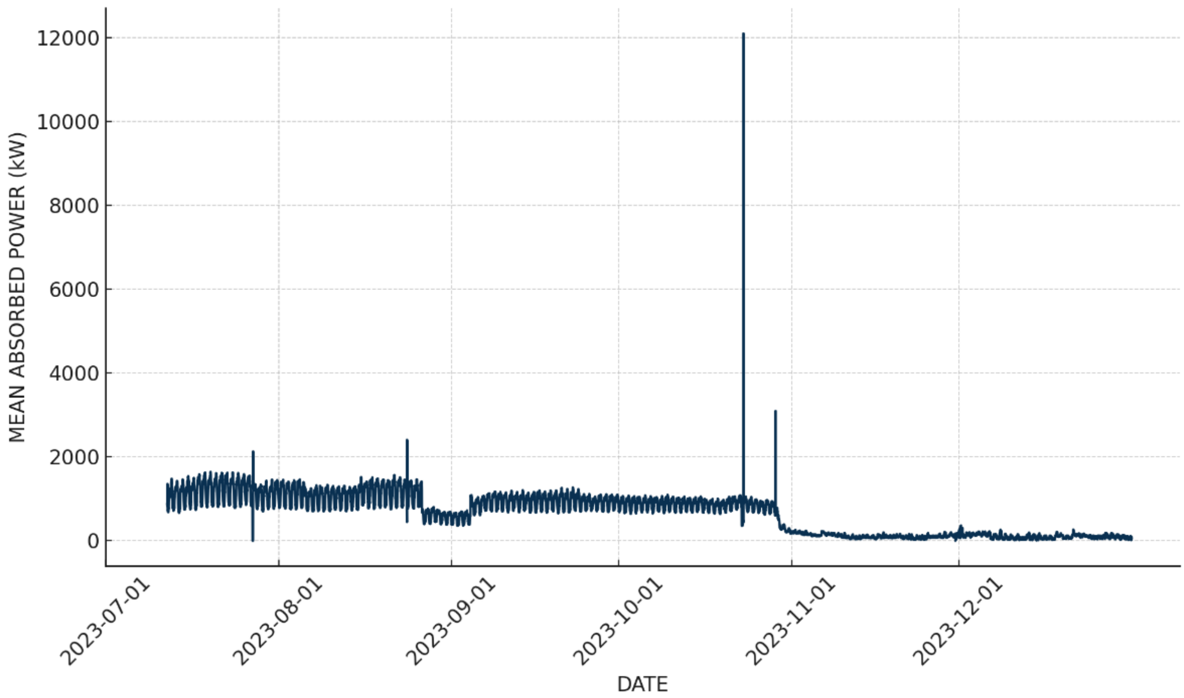

Figure 4.3: Data from existing resort

In this dataset, some values were flagged as unreasonably high or low, attributed to inaccurate measurements. A pattern was identified starting from July 23rd, where the daily electricity consumption displayed mirrored behavior. For instance, the daily electricity consumption on July 22nd matched that of July 24th, and July 21st matched that of July 25th, following this pattern. Figure 4.4 illustrates how this pattern was applied to fill in the missing data.

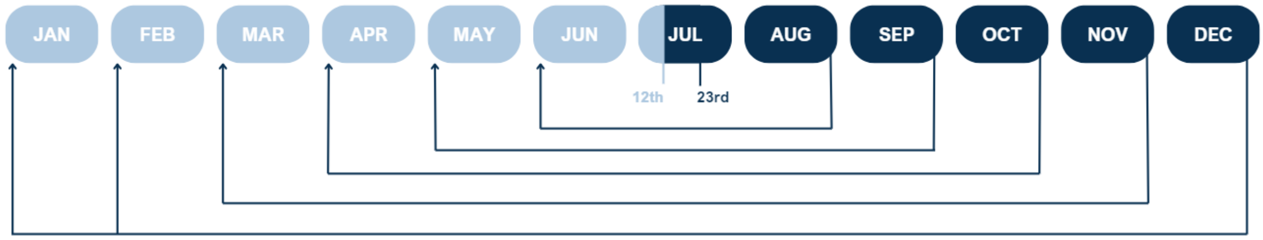

Figure 4.4: Data Recovering Method

The two resorts, the existing one and the case-study, have different guest capacities. The annual capacity rate of the existing resort was first calculated using the Equation 4.1.

$$Guest\ capacity\ (\%) = \frac{Daily\ guest\ capacity\ (existing)}{Maximum\ guest\ capacity\ (existing)} \tag{4.1}$$

According to this rate, the daily guest capacity of the case-study resort was calculated by Equation 4.2.

$$\begin{aligned} &Number\ of\ guests\ per\ day\ (case\ study) = \\ &= Guest\ capacity\ (\%) * Maximum\ capacity\ (case\ study) \end{aligned} \tag{4.2}$$

By knowing the daily guest capacity and electricity demand load of the existing resort, it was feasible to estimate the electricity demand load for the case study resort. The annual energy demand, calculated with an hourly resolution, was determined using Equation 4.3.

$$\begin{aligned} &E_{case\ study}\ (kWh) = \\ &= \frac{Hourly\ consuption\ (existing) * Number\ of\ guests\ per\ day\ (case\ study)}{Daily\ guest\ capacity\ (existing)} \end{aligned} \tag{4.3}$$

Figure 4.5 represents the annual electricity demand profile of the case study resort. This updated figure reflects the corrections made to the erroneous data, ensuring that the analysis is based on a reliable depiction of the resort's energy consumption.

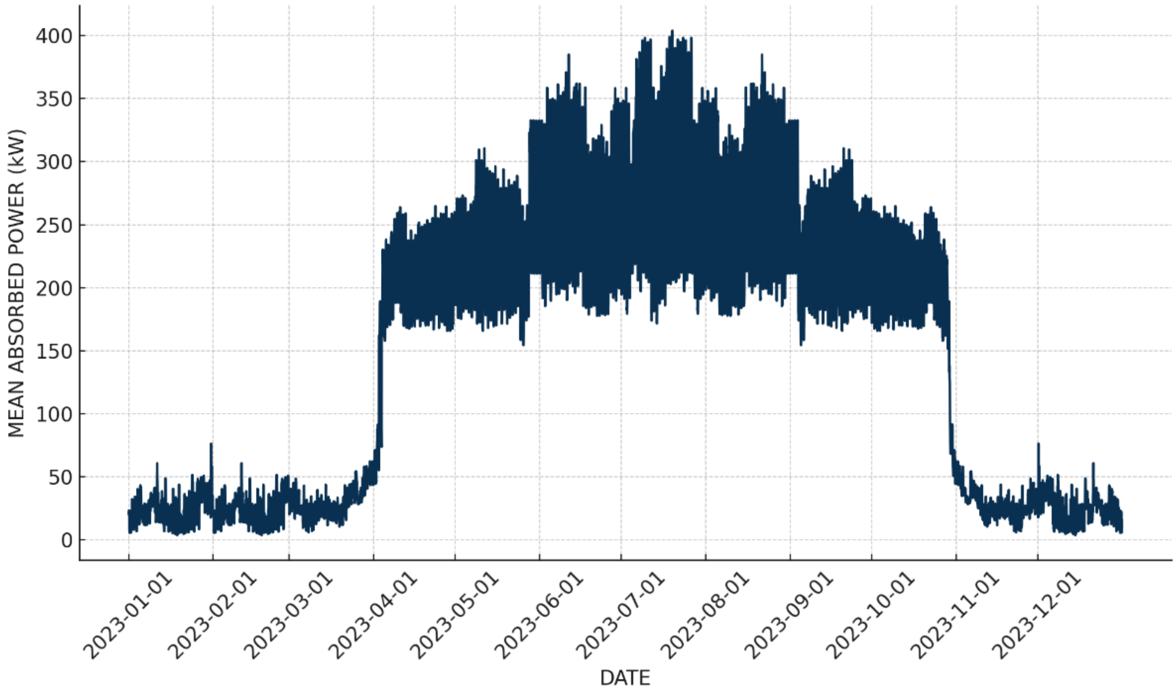

Figure 4.5: Annual load demand

In summary, the average daily AC load was 3,715 kWh with a peak load of 403.87 kW in July.

Figure 4.6 presents the average monthly load profile, showing higher overall demand during the summer season (April to October), when the case study resort is operating.

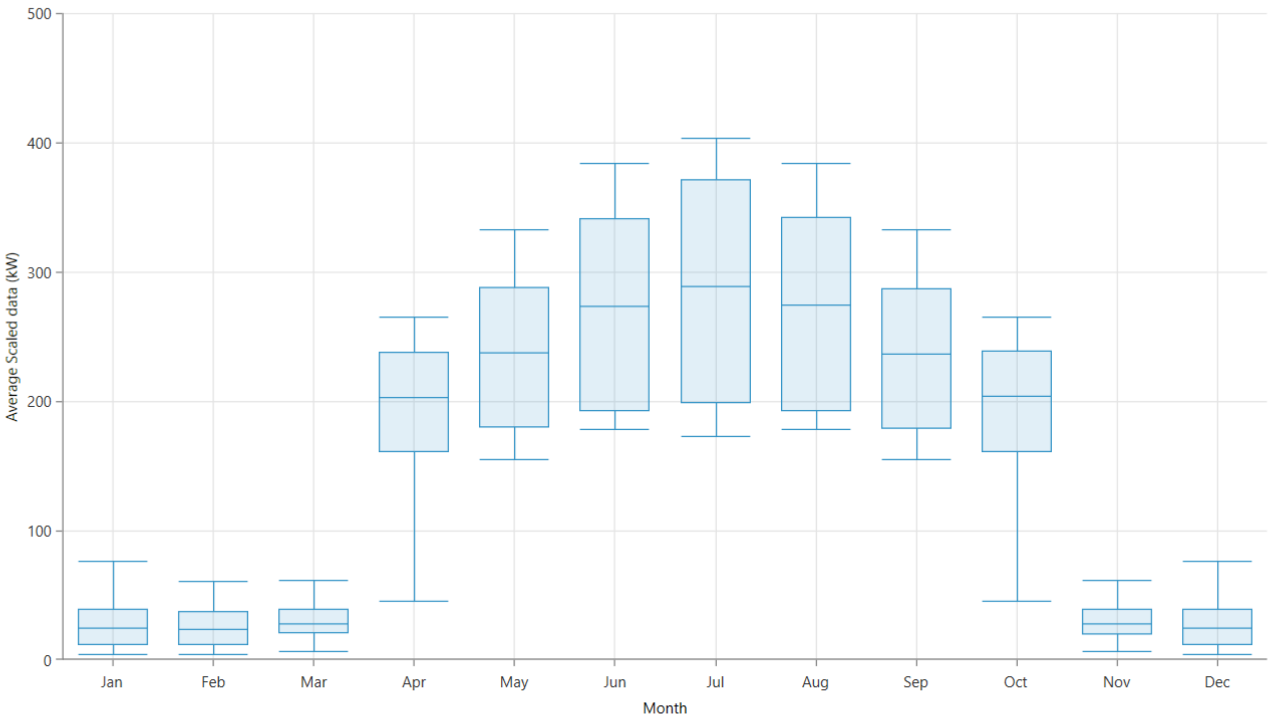

Figure 4.6: Average monthly load

Figure 4.7 displays the average daily load profile for each month.

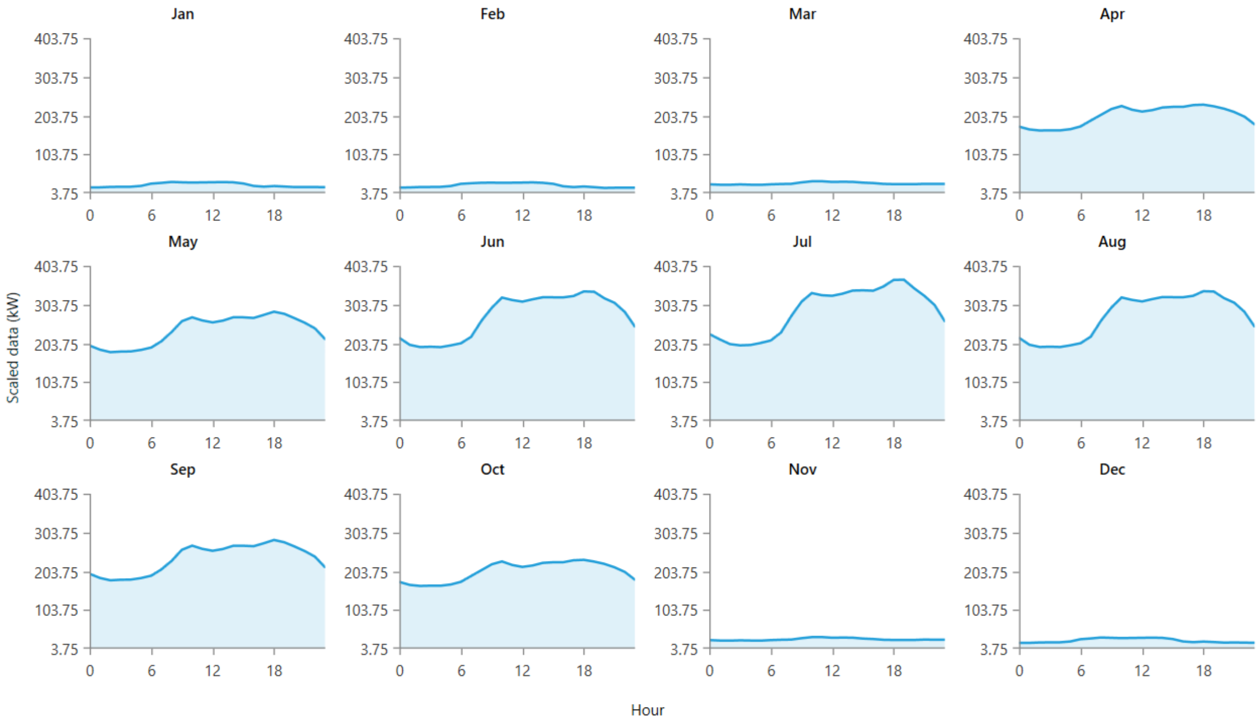

Figure 4.7: Average daily load profile by month

During the months when the case study resort is operational, peak loads occur between 9AM and 6PM, while lower loads are observed in the early morning and late evening hours. In the off-season months, the daily load remains low, with peak around 11AM.

4.3 Proposed Microgrid

A stand-alone fully powered by RES microgrid has been examined in this study. This system comprises three main components, Photovoltaic system (PV), Battery Energy Storage System (BESS) and Power to Hydrogen to Power (P2H2P) system, which includes an electrolyzer, a Fuel Cell (FC) and a hydrogen storage tank. Three scenarios are examined to evaluate different sizing options and combinations of these components. The objective is to determine the key technical characteristics of the system in each scenario that leads to the best financial results, and to compare the scenarios in terms of their economic performance.

4.4 Scenarios

In this study, three scenarios are evaluated for the stand-alone microgrid over a 25-year project lifetime. These scenarios explore different configurations and sizing of the PV system, BESS, and P2H2P system to determine the most technically and economically feasible solution for powering the resort entirely through renewable energy. In addition to these three scenarios, a fourth scenario is also considered. This scenario investigates the CAPEX required for a potential grid connection, analyzing the conditions where connecting the resort to the grid would be a more financially viable solution.

The scenarios are:

- **Scenario 1 (S.1):** Solar PV and BESS
- **Scenario 2 (S.2):** Solar PV and P2H2P system (electrolyzer, Fuel Cell, H_2 tank)
- **Scenario 3 (S.3):** Solar PV, BESS and P2H2P system (electrolyzer, Fuel Cell, H_2 tank)
- **Scenario 4 (S.4):** Grid-connection

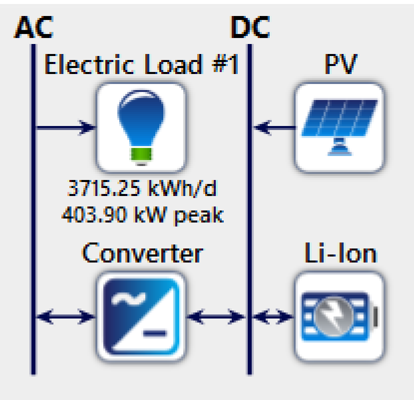

Figure 4.8: Scenario 1, Solar PV and BESS

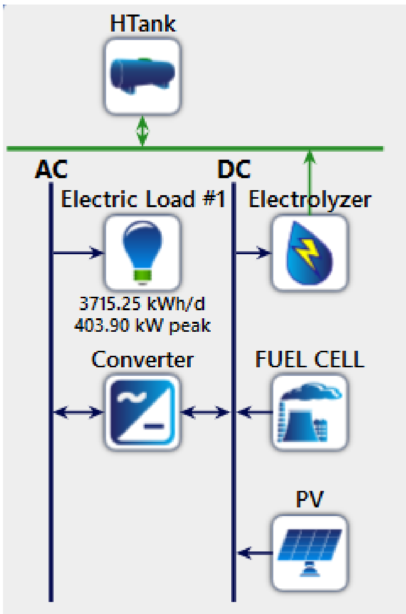

Figure 4.9: Scenario 2, Solar PV and P2H2P system (electrolyzer, FC, H_2 tank)

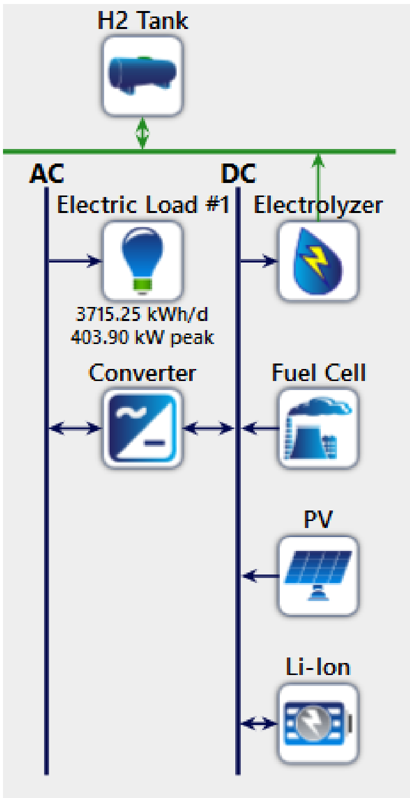

Figure 4.10: Scenario 3, Solar PV, BESS and P2H2P system (electrolyzer, FC, H_2 tank)

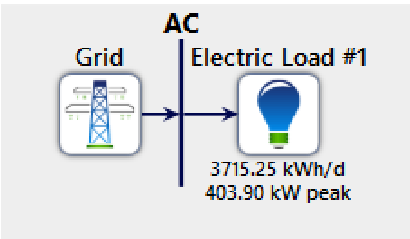

Figure 4.11: Scenario 4, Grid-connection

The scenario 1 schematic, which uses a Load-Following (LF) dispatch strategy and solar PV and Li-Ion BESS to create a 100% RE system, is depicted in Figure 4.8. Simulation constraints were adjusted so that at least 99.98% of the load demand could be satisfied. The BESS system was chosen to have at least two hours of autonomy. HOMER Pro sizes and optimizes the system's component parts to achieve the minimum NPC possible.

Figure 4.9 illustrates the schematic of scenario 2, which is a RE-P2H2P system consisting of solar PV, electrolyzer, fuel cell, and H_2 tank with LF dispatch strategy. The constraints of the simulation were the same as those chosen for Scenario 1. HOMER Pro sizes and optimizes the system's component parts to produce the lowest NPC feasible. The H_2 tank was completely empty at the beginning of the simulation. The size of the fuel cell was left to be optimized by the software during the simulation.

The schematic of scenario 3 is shown in Figure 4.10 and represents a HRES consisting of solar PV, electrolyzer, fuel cell, H_2 tank and Li-Ion BESS with LF dispatch strategy. The BESS system is chosen to have a minimum of two hours autonomy and is optimized by HOMER Pro. Fuel cell's size is optimized to utilize the maximum excess energy in the remote microgrid. The simulation constraints were identical to those in S.1 and S.2. System's components are sized and optimized by HOMER Pro to achieve the minimum NPC possible.

Figure 4.11 represents the schematic scenario S.4, which demonstrates a grid connected AC system. In this instance, the financial viability of connecting a remote location to the grid rather than forming a HRES is examined by looking at the LCOE. Various initial interconnection investment costs are considered to determine the threshold at which it becomes more cost-effective to develop a self-sustained microgrid using renewable energy sources instead of relying on grid connection.

4.5 Input Data

In this section, the input data of each component used in HOMER Pro simulations is described.

For scenarios S.1, S.2 and S.3 components' specifications, capital and operating costs (CAPEX and OPEX) were imported from the HOMER Pro library and adjusted to the costs in the literature reviewed and the market, proposed by Z. Medghalchi at al. [27] and B. D. James at al. [28].

A generic flat plate PV system was chosen to be optimized by HOMER Pro. For each scenario, four sub-scenarios were analyzed by adjusting the panel slope to 10, 20, 30 and 40 degrees. The sub-scenario with the slope that resulted in the lowest NPC was then chosen. The BESS was composed of Lithium-ion technology with SoC from 20% to 80%. The BESS size is optimized by the software in each simulation, as well as the size of the converter based on the maximum energy level of the system. In scenarios S.2 and S.3 where a fuel cell (FC) is simulated as part of the microgrid, multiple values for the FC size are entered with a step of 50 kW.

The financial modelling inputs are shown in Table 4.1.

Table 4.1: Financial Input Data

Specification	**Unit**	**Value**	**Reference**
PV Capital Cost	€/kW	1547	[27]
PV Replacement Cost	€/kW	1547	Author estimate
PV O & M Cost	€/kW/year	24	[27]
Panel Slope	degrees (°)	10 to 40	Author estimate
Derating factor	%	80	HOMER Pro Default
BESS Capital Cost	€/kWh	550	[27]
BESS Replacement Cost	€/kWh	550	Author estimate
BESS O & M Cost	€/kWh/year	10	[27]
Fuel Cell Capital Cost	€/kW	3947	[27]
Fuel Cell Replacement Cost	€/kW	3947	Author estimate
Fuel Cell O & M Cost	€/kW/op. hour	0.018	[28]
Electrolyzer Capital Cost	€/kW	4600	[27]
Electrolyzer Replacement Cost	€/kW	4600	Author estimate
Electrolyzer O & M Cost	€/kW/year	138	[27]
H_2 tank Capital Cost	€/kg	470	[27]
H_2 tank Replacement Cost	€/kg	470	Author estimate
H_2 tank O & M Cost	€/kg	9.4	[27]

In scenario S.4, the connection between the mainland grid and the remote microgrid is examined. Different values for the initial capital cost of interconnection are used as input data to identify the point at which a 100% renewable energy microgrid becomes more financially viable than connecting the remote location to the grid. In this scenario, the initial interconnection investment is increasing by increments of 100,000 € in each simulation and stops when the S.4 LCOE is higher than the lowest LCOE of scenarios S.1, S.2, and S.3.

The input data for scenario S.4 is shown in Table 4.2.

Table 4.2: Input Data S.4

Category	Specification	Unit	Value	Reference
Grid Extension cost	Grid capital cost	(€)	100,000	Range
Rate Definition	Rate 1	(€/kWh)	0.198	Author estimate
	Rate 2	(€/kWh)	0.159	Author estimate
	Rate 3	(€/kWh)	0.146	Author estimate
Emissions	Carbon Dioxide	(g/kWh)	632	HOMER Pro Default
	Sulfur Dioxide	(g/kWh)	2.74	HOMER Pro Default
	Nitrogen Oxides	(g/kWh)	1.34	HOMER Pro Default
Emissions Penalties	Carbon Dioxide Penalty	(€/t)	85	EU ETS
	Sulfur Dioxide Penalty	(€/t)	100	EU ETS
	Nitrogen Oxides Penalty	(€/t)	50	EU ETS

Grid's rates were determined according to Greece's grid prices in 2023. The Grid Rate Schedule was formed as shown in Figure 4.12.

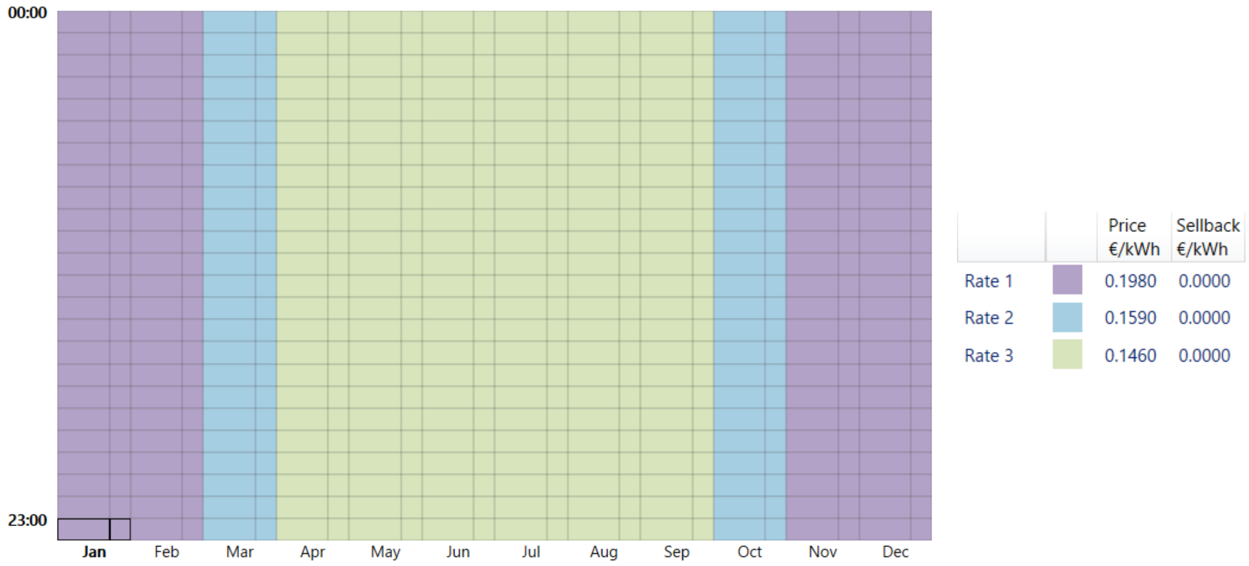

Figure 4.12: Grid Rate Schedule

The emissions penalties have been determined according to the European Union Emissions Trading System (EU ETS).

In all scenarios the following constraints were added shown in Table 4.3.

Table 4.3: Constraints for all scenarios

Specification	Unit	Value	Reference
Location	Latitude, Longitude	40°13'25''N 23°47'06''E	Author estimate
Project's lifetime	years	25	Author estimate
Discount rate	%	8	HOMER Pro Default
Inflation rate	%	2	HOMER Pro Default
Maximum annual capacity shortage	%	0.02	Author estimate
Minimum renewable fraction	%	100	Author estimate
Real discount rate	%	5.88	Author estimate
System's precision	%	0.01	HOMER Pro Default
Net Present Cost precision	%	0.01	HOMER Pro Default

Chapter 5: Results

5.1 Introduction

This chapter discusses the simulation results of all four scenarios outlined in Chapter 4. Beginning with the optimization results, then moving on to the sensitivity analysis results. HOMER Pro analyzes various component sizes for each of the four scenarios and chooses components that meet at least 99.98% of load requirements. The technical, economic, and emission related aspects are used to evaluate and compare the four scenarios.

5.2 Results for Scenarios S.1, S.2, S.3

5.2.1 Scenario 1 (S.1): Solar PV and BESS

Scenario S.1 analyzes a solar PV and BESS microgrid with at least 99.98% capacity shortage. The panel slope that resulted in the lowest NPC was 10°.

The optimization results of scenario S.1 with panel slope at 10° are shown in Table 5.1.

Table 5.1: Optimization Results S.1

Optimization Results S.1 (Solar PV and BESS)			
System Components	Generic flat plate PV (10° slope)	(MW)	3.52
	Li-Ion BESS	(MWh)	9.0
	Converter	(kW)	439
Electrical values	Generic flat plate PV production	(kWh/year)	4,518,133
	Excess Electricity	(kWh/year)	3,000,000
	Excess Electricity	(%)	66.8
	Unmet Electric Load	(kWh/year)	1,388
	Unmet Electric Load	(%)	0.102
	Capacity Shortage	(kWh/year)	1,613
	Capacity Shortage	(%)	0.119
	Renewable Fraction	(%)	100
BESS	Autonomy	(hours)	49.7
	Usable Nominal Capacity	(MWh)	7.686
Emissions	Carbon Dioxide produced	(kg/yr)	0
	Sulfur Dioxide produced	(kg/yr)	0

	Nitrogen Oxides produced	(kg/yr)	0
Finance values	Total Net Present Cost (Total NPC)	(million €)	13.2
	System initial capital cost (CAPEX)	(million €)	10.8
	Levelized Cost of Energy (LCOE)	(€/kWh)	0.753
	Annualized System O&M cost	(€/year)	180,555

The optimal configuration for this scenario with the lowest NPC consists of an approximately 3.5 MW generic flat plate PV, 9MWh Li-Ion BESS (20-80% SoC) and 439 kW converter. 99.89% of the total electrical load managed to be covered by the 100% RE system. The results show that 66.8% of the total PV production is not used.

Figure 5.1 shows the average daily solar PV production (kW) for every month of the year. As expected, production varies between 6AM and 6PM, with the peak power output occurring at midday, forming a bell-shaped figure. In January and December, the peak power output occurs at around 10AM and 14PM respectively.

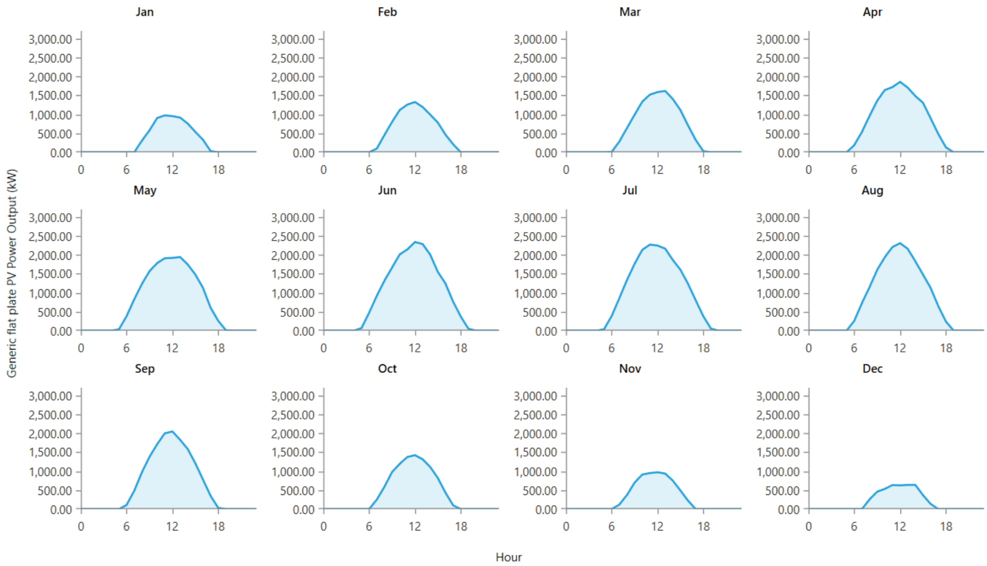

Figure 5.1: DMap Generic flat PV Annual Power Output

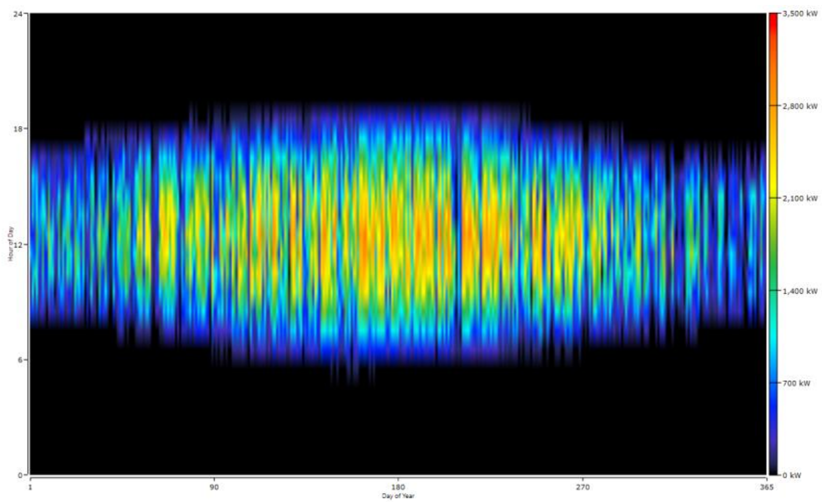

Figure 5.2: DMap Generic flat PV Annual Power Output

As illustrated in Figure 5.3 and Figure 5.4, the peak month for average RE production at this location is June, which coincides with the highest average global irradiation and relatively low temperatures.

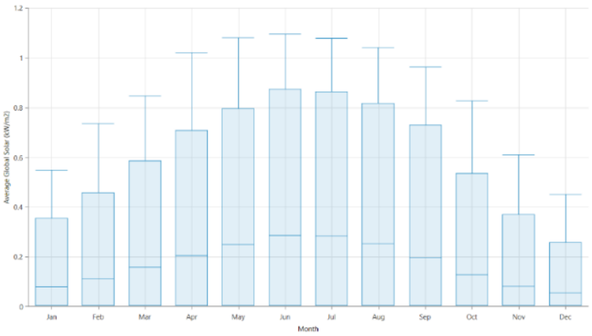

Figure 5.3: Global Solar Monthly Averages.

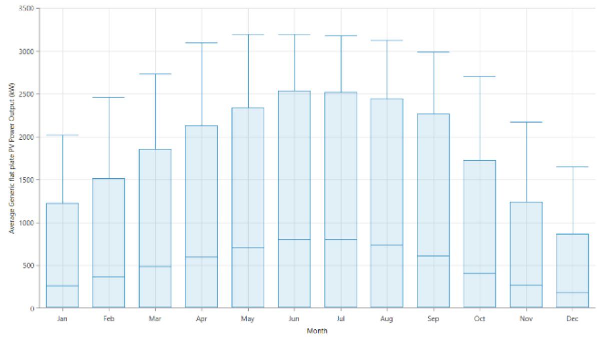

Figure 5.4: Generic flat PV Power Output Monthly Averages.

Figure 5.5 shows the average State of Charge (SoC) of the 9MWh BESS over a 24-hour period for each month of the year, reflecting seasonal and daily variations. Each subplot represents a month from January to December, with the SoC percentage on the y-axis and time of day in hours on the x-axis. During the summer months, when the resort is hosting guests, the SoC varies, with dips in the morning and evening suggesting that the battery discharges to meet energy demand, due to the lack of PV production at that time of the day. The BESS charges during the time of the day with high PV production. In winter months (November to March) the SoC remains almost stable to 100%, since the load demand is very low and can be covered directly from the PV system. The BESS has 49.7 hours of autonomy, while the usable nominal capacity is 7.686 MWh.

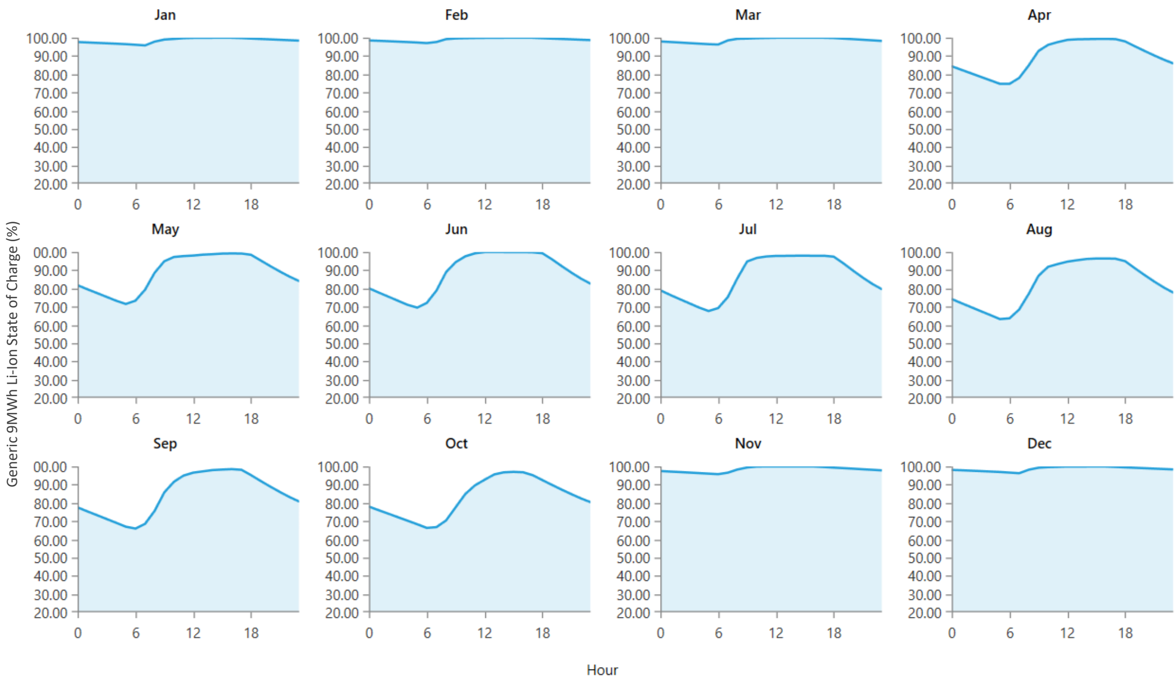

Figure 5.5: Li-Ion BESS 9 MWh State of Charge Average Daily Profile

In Figure 5.6 the y-axis represents the hour of the day, while the x-axis represents the day of the year. During the summer months the SoC ranges between 100% (11AM to 6PM) and 80 - 60% during the late evening and early morning hours. It is shown that the BESS discharges to 20% on August 1st. An unmet electric load of 1,388 kWh is detected on this day, as shown in Figure 5.7.

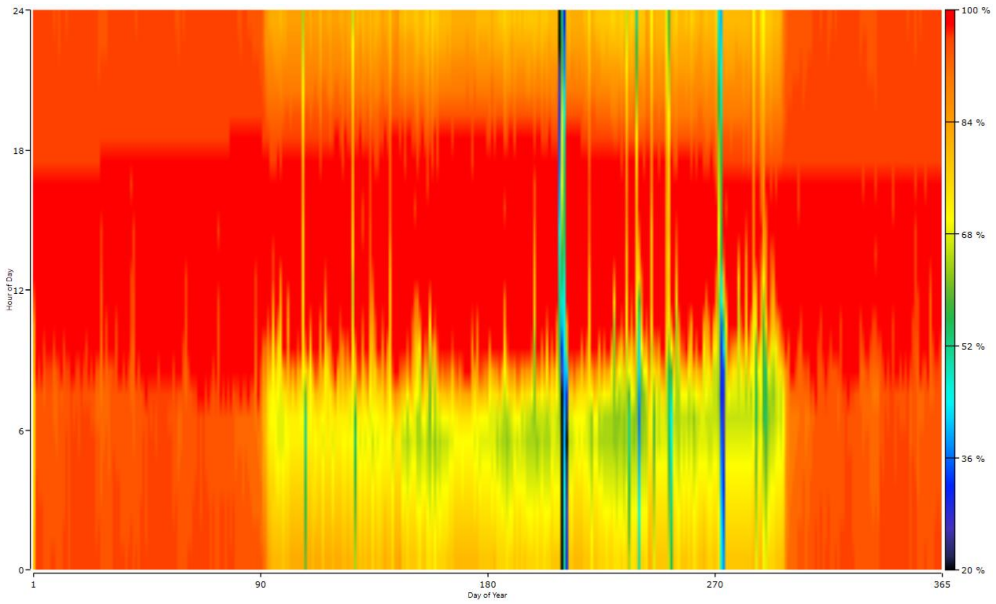

Figure 5.6: DMap BESS 9 MWh annual State of Charge

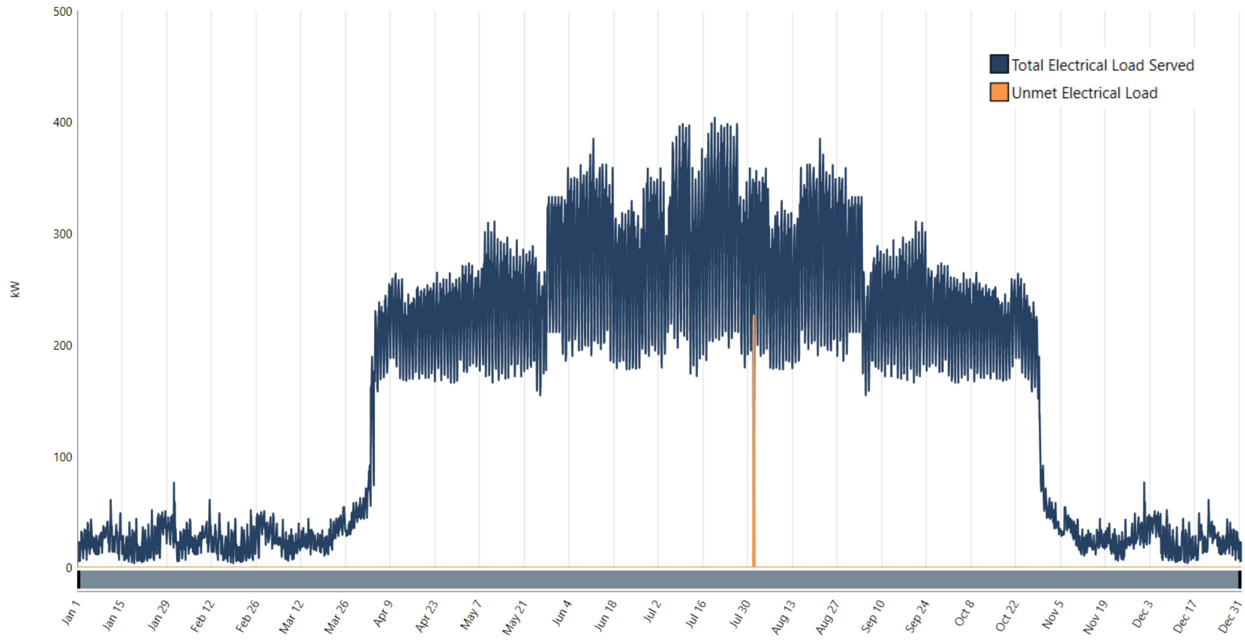

Figure 5.7: Unmet load compared to Total Electrical Load Served

Figure 5.8 illustrates the system operation of the PV - BESS in scenario 1 for one week in a typical solar radiation summer month of June. The plot demonstrates the contribution of the PV production in covering the load demand, while also showing the BESS contribution on covering the hours where generation is not possible.

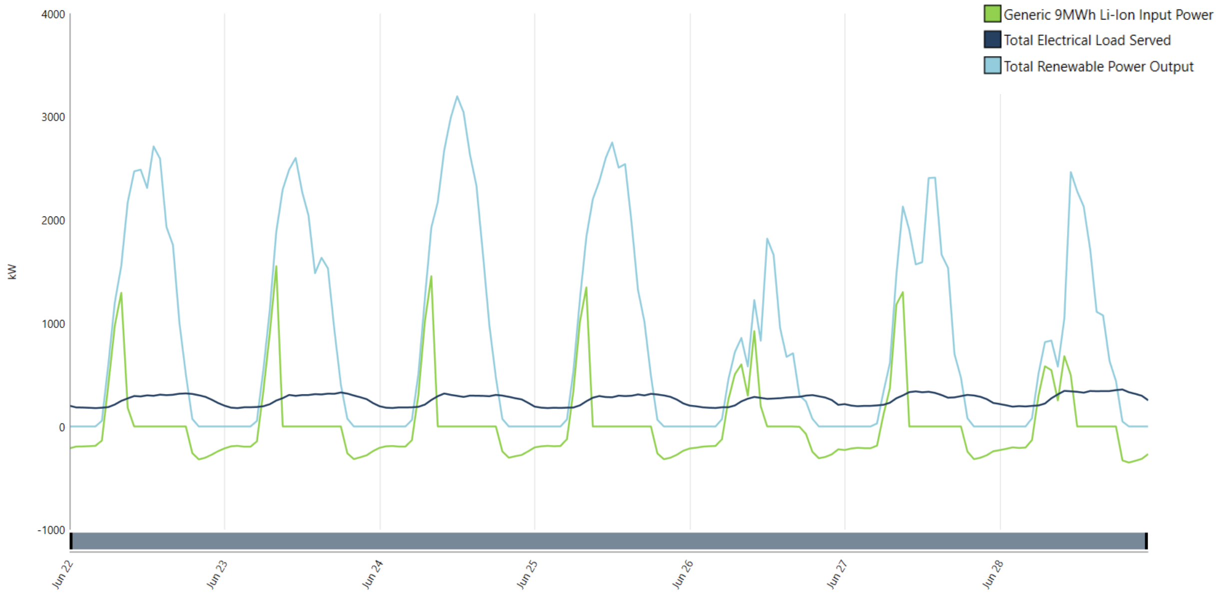

Figure 5.8: One week load, PV production & BESS profile (June)

Figure 5.9 illustrates the system operation for scenario S.1 for one week in a lower solar radiation winter month of January.

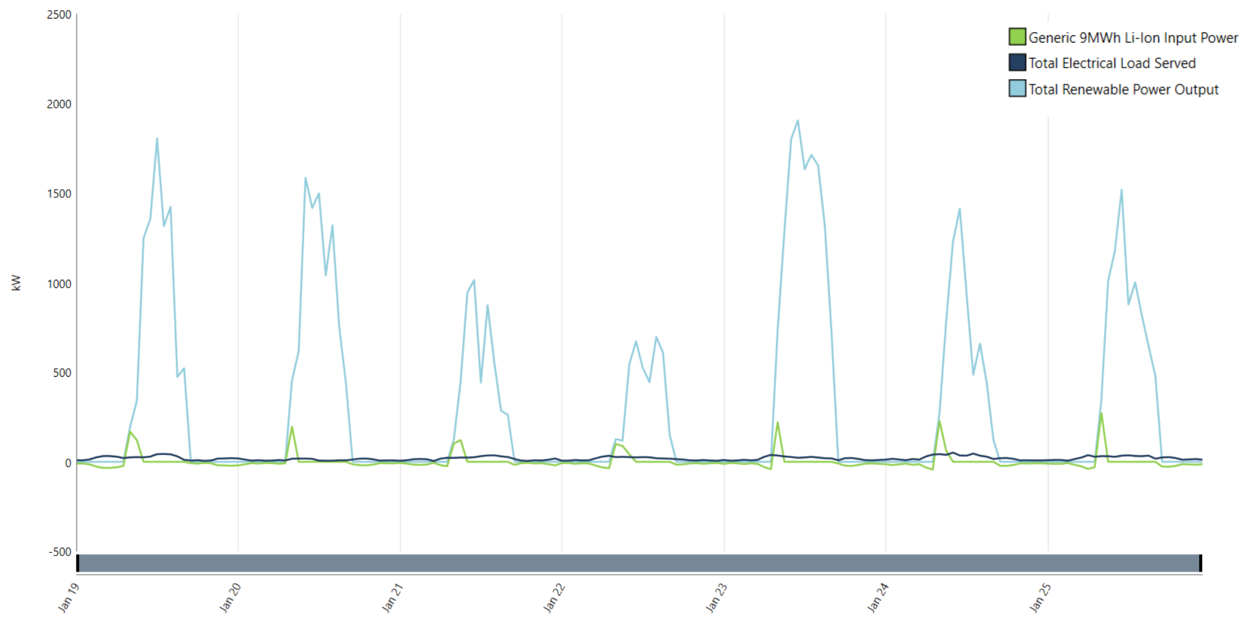

Figure 5.9: One week load, PV production & BESS profile (January)

The total NPC for scenario S.1 is 13.2 million euros. The allocation of funds spent during the project's lifetime are shown in Figure 5.10. The system's initial CAPEX is 10.8 million euros, while OPEX is 180,555 €/year, while the LCOE in this case is estimated to be 0.753€/kWh during the project's lifetime (25 years). The system does not appear any emission harmful for the environment.

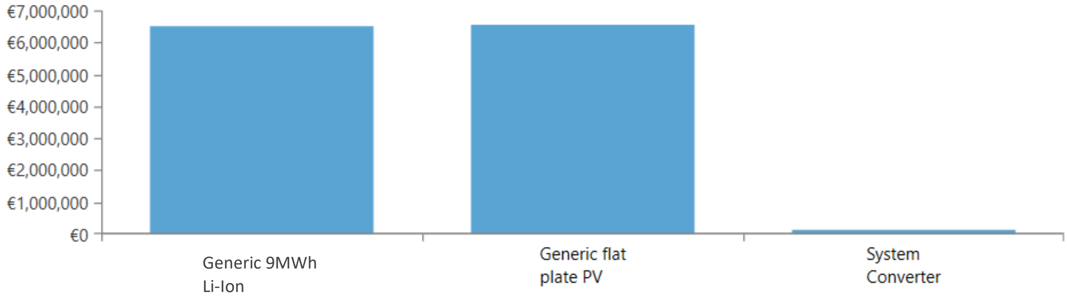

Figure 5.10: Scenario S.1 - NPC

5.2.2 Scenario 2 (S.2): Solar PV and P2H2P system (electrolyzer, Fuel Cell, H_2 tank)

Scenario S.2 analyzes a Solar PV and P2H2P system with electrolyzer, fuel cell, and hydrogen tank. As shown in Figure 5.11 HOMER Pro optimization software was unable to identify any financially viable combination of components for scenario 2. This indicates that the chosen combination was neither technically nor financially feasible, and the Net Present Cost (NPC) could not be reduced sufficiently to make the scenario worthwhile for consideration.

HOMER was unable to find a system which meets the demand.
No feasible solutions.

Here are some reasons why this may have happened:
- Not enough generation capacity
- Not enough annual capacity shortage allowed
- Emissions limitations
- Minimum renewable fraction

Click the "Calculation Report" button for details

Figure 5.11: Scenario 2, no feasible solution

This result of scenario S.2 simulation provides valuable information on P2H2P systems. Although these types of systems are selected for seasonal storage purposes, it seems that they cannot operate without a BESS in this type of load demand. This can be explained due to the low efficiency of P2H2P systems compared to BESS, combined with the high cost, as the technology is still new and developing.

5.2.3 Scenario 3 (S.3): Solar PV, BESS and P2H2P system (electrolyzer, Fuel Cell, H_2 tank)

Scenario S.3 analyzes a solar PV, BESS and P2H2P system with fuel cell, electrolyzer and hydrogen storage. The system is obligated to have at least 99.98% capacity shortage. The panel slope that resulted in the lowest NPC was 40°.

The optimization results of scenario S.3 with panel slope at 40 ° are shown in Table 5.2.

Table 5.2: Optimization Results S.3

Optimization Results S.3 (Solar PV, BESS and P2H2P system (electrolyzer, Fuel Cell, H2 tank))			
System Components	Generic flat plate PV	(MW)	3.161
	Li-Ion BESS	(MWh)	4.5
	Fuel Cell	(kW)	900
	Electrolyzer	(kW)	257
	Hydrogen tank	(kg)	2,850
	Converter	(kW)	474
Electrical values	Total electricity production	(kWh/year)	4,253,000
	Total consumption	(kWh/year)	1,800,000
	Excess Electricity	(kWh/year)	2,322,032
	Unmet Electric Load	(kWh/year)	945
	Unmet Electric Load	(%)	0.06
	Capacity Shortage	(kWh/year)	1,120
	Capacity Shortage	(%)	0.0826
	Renewable Fraction	(%)	100
Generic flat plate PV	Generic flat plate PV production	(kWh/year)	4,219,651
Li-Ion BESS	Autonomy	(hours)	23.9
	Usable Nominal Capacity	(MWh)	3.7
Fuel Cell	Fuel Cell production	(kWh/year)	32,849
	Hours of Operation	(hrs/year)	165
	Number of Starts	(starts/year)	40
	Fuel consumption	(kg)	6,900
Electrolyzer	Electrolyzer consumption (input energy)	(kWh/year)	430,754
	Total production	(kg/year)	9,282

Hydrogen tank	Energy storage capacity	(kWh)	95,000
	Tank autonomy	(hours)	614
Emissions	Carbon Dioxide produced	(kg/yr)	0
	Sulfur Dioxide produced	(kg/yr)	0
	Nitrogen Oxides produced	(kg/yr)	0
Finance values	Total Net Present Cost (Total NPC)	(million €)	15.6
	System initial capital cost (CAPEX)	(million €)	13.6
	Levelized Cost of Energy (LCOE)	(€/kWh)	0.88
	Annualized System O&M cost	(€/year)	187,310

A configuration of an approximately 3.2 MW generic flat plate PV, 4.5 MWh Li-Ion BESS (20 - 80% SoC), 900 kW fuel cell, 257 kW electrolyzer, 2.8 tones hydrogen tank and 474 kW converter.

In scenario S.3, 99.94% of the total electrical load managed to be covered by the HRES. The results show that around 50% of the total electricity production is not used.

Figure 5.12 shows the average daily solar PV production (kW) for every month of the year. PV production follows the same pattern as scenario S.1, but due to the lower rated capacity the total energy production is lower.

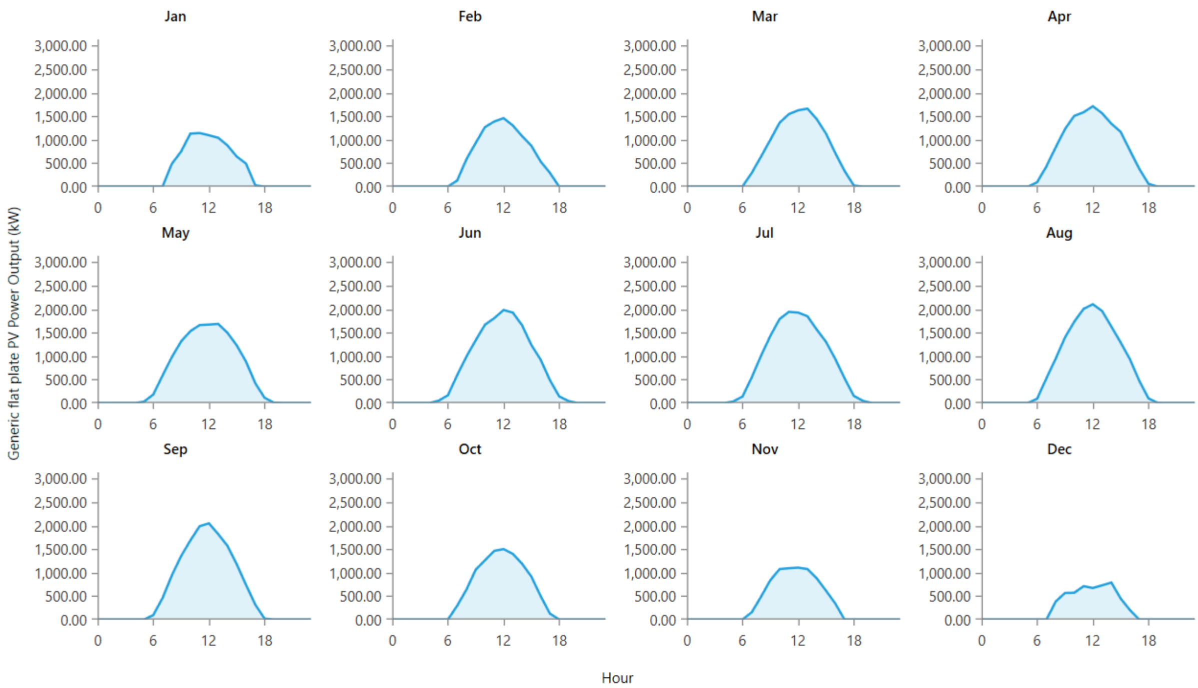

Figure 5.12: Generic flat plate PV Power Output Average Daily Profile

Figure 5.13 indicates the PV annual power output for 24 hours.

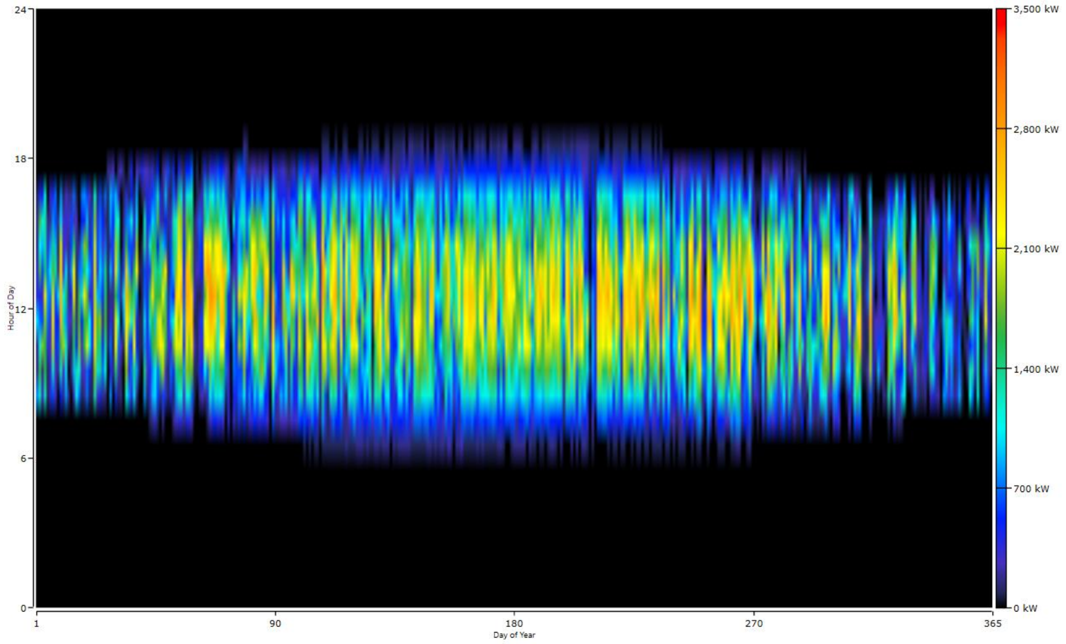

Figure 5.13: DMap Generic flat PV Annual Power Output

Figure 5.14 illustrates the average State of Charge (SoC) of the 4.5 MWh BESS over a 24-hour period for each month of the year, with the SoC percentage on the y-axis and time of day in hours on the x-axis. Since BESS capacity in scenario S.3 is significantly lower than S.1, the battery has larger Depth of Discharge (DoD) during the summer months. The BESS has almost 24 hours of autonomy, while the usable nominal capacity is 3.7 MWh.

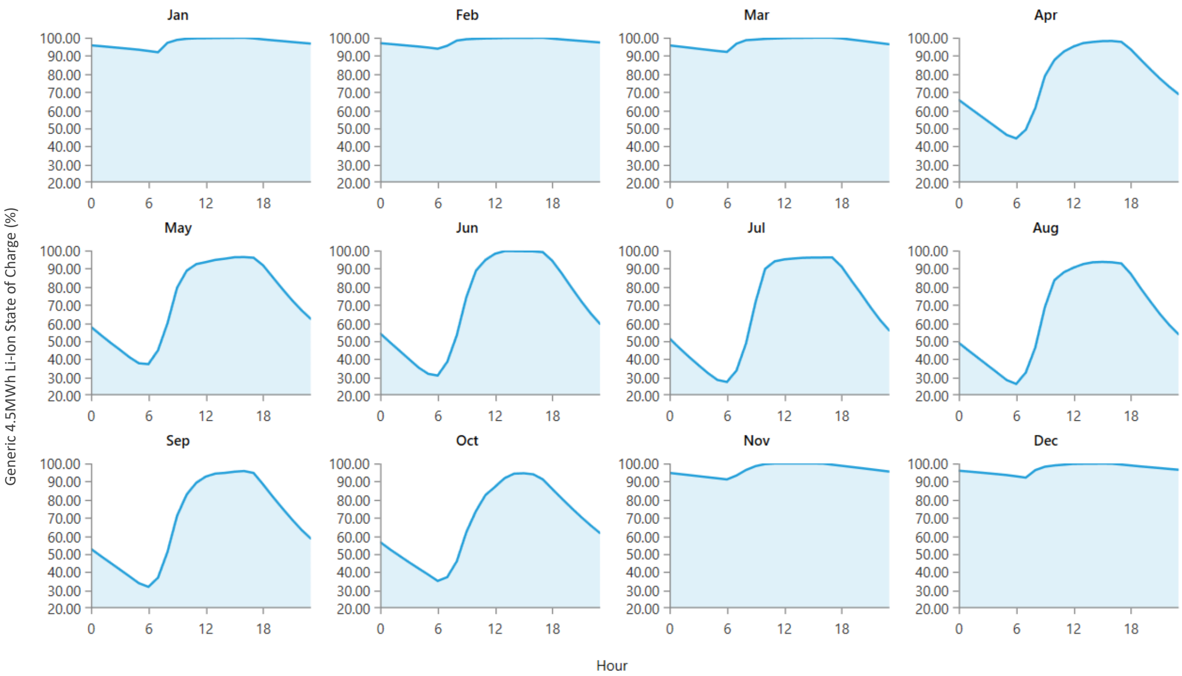

Figure 5.14: Li-Ion BESS 4.5 MWh State of Charge Average Daily Profile

Figure 5.15 makes clear that in scenario S.3 there are multiple days during the year where the BESS discharges fully (to 20%) and the system needs to cover this lack of power by operating the fuel cell.

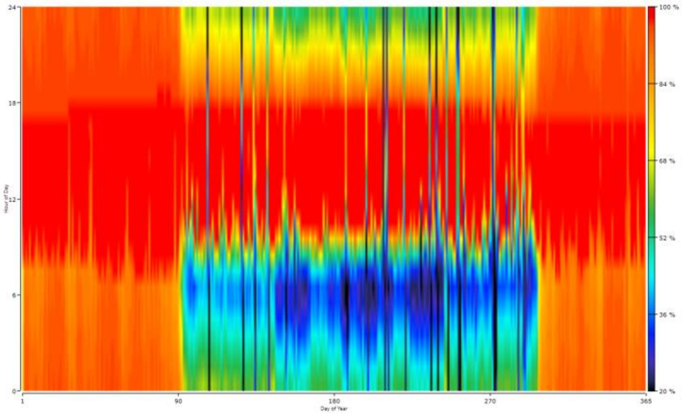

Figure 5.15: DMap BESS 4.5 MWh annual State of Charge

As shown in Figure 5.16, the fuel cell does not operate at all during the winter months, since the system can cover its load demand by the PV - BESS configuration alone. During the summer months, the FC operates on average during the early mornings and late nights. Due to the highest load demand during July, the FC operates on average all day, with a peak at around 8PM, when the PV production is low.

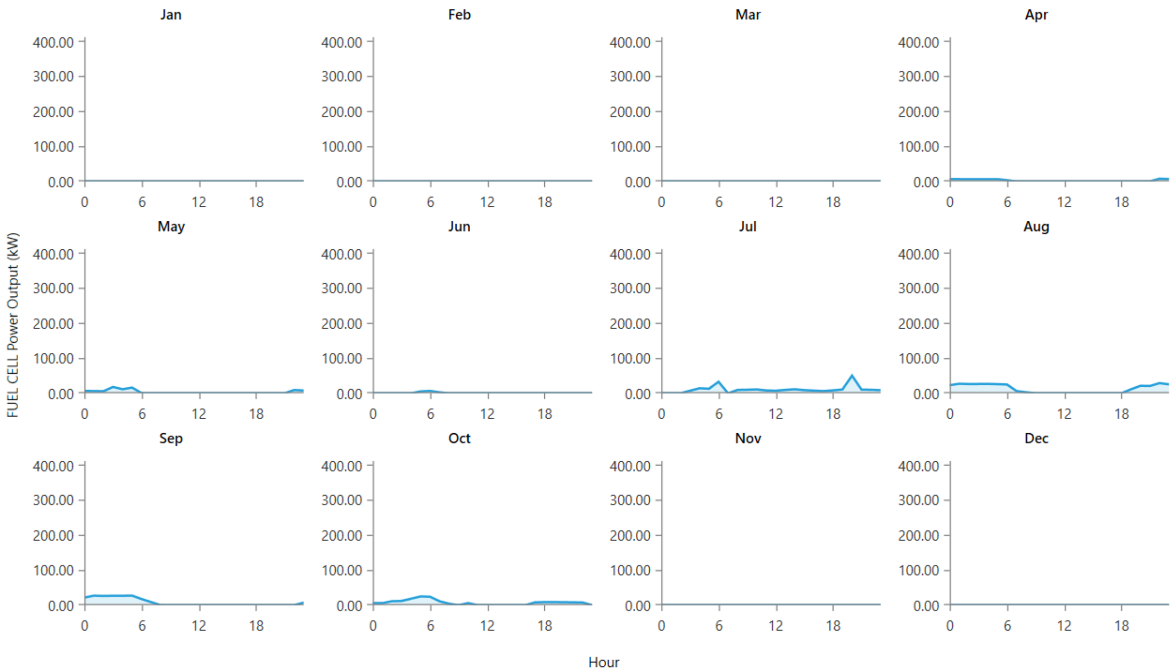

Figure 5.16: Fuel Cell Power Output Average Daily Profile

Figure 5.17 explains in deeper detail the monthly fluctuation of FC power output, while Figure 5.18 shows the 40 different starts of the FC during the year. The FC operated in total of 165 hours annually, produced 32,849 kWh/year by consuming almost 7 tons of hydrogen.

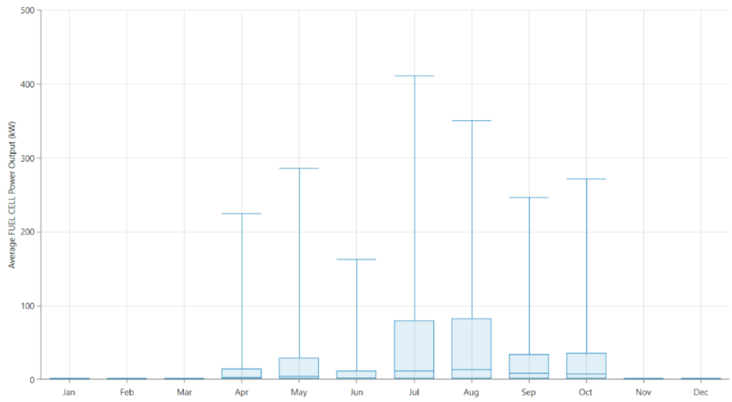

Figure 5.17: Fuel Cell Power Output Monthly Profile

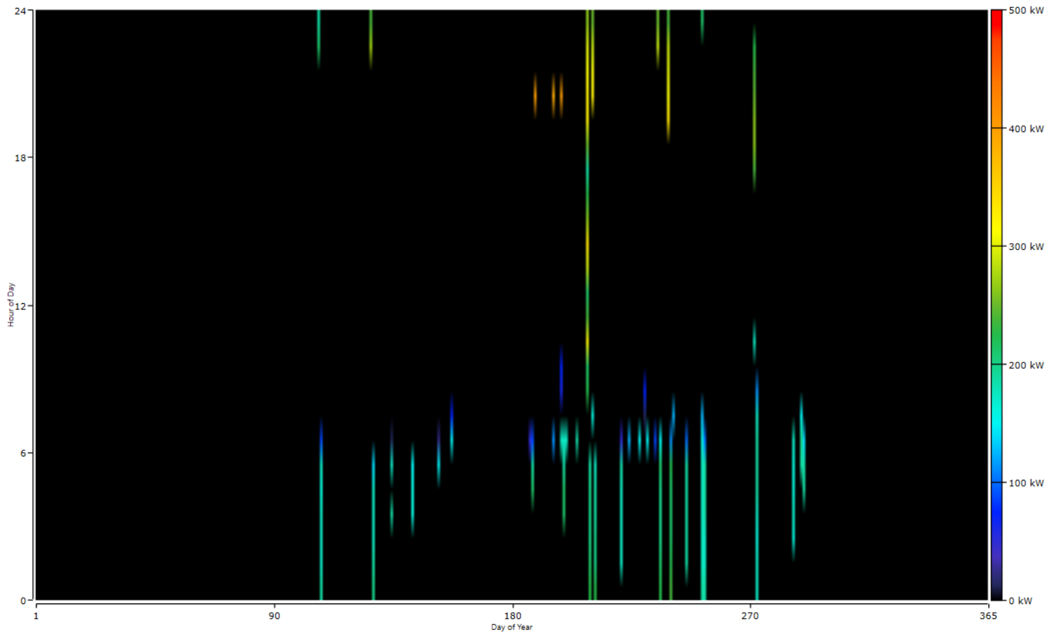

Figure 5.18: Fuel Cell Power Output Annual Profile

The electrolyzer consumed in total 430,754 kWh/year to produce 9.3 tons of hydrogen annually. Figure 5.19 illustrates the average daily input profile for each month. Since the electrolyzer was powered by the energy generated by the PV system, its input pattern resembles a bell curve, similar to the PV system's production. During the summer months, the electrolyzer received less energy for hydrogen production due to higher load demand, leaving limited excess energy for this purpose.

Figure 5.20 shows that the electrolyzer operated at maximum capacity more frequently during the winter months.

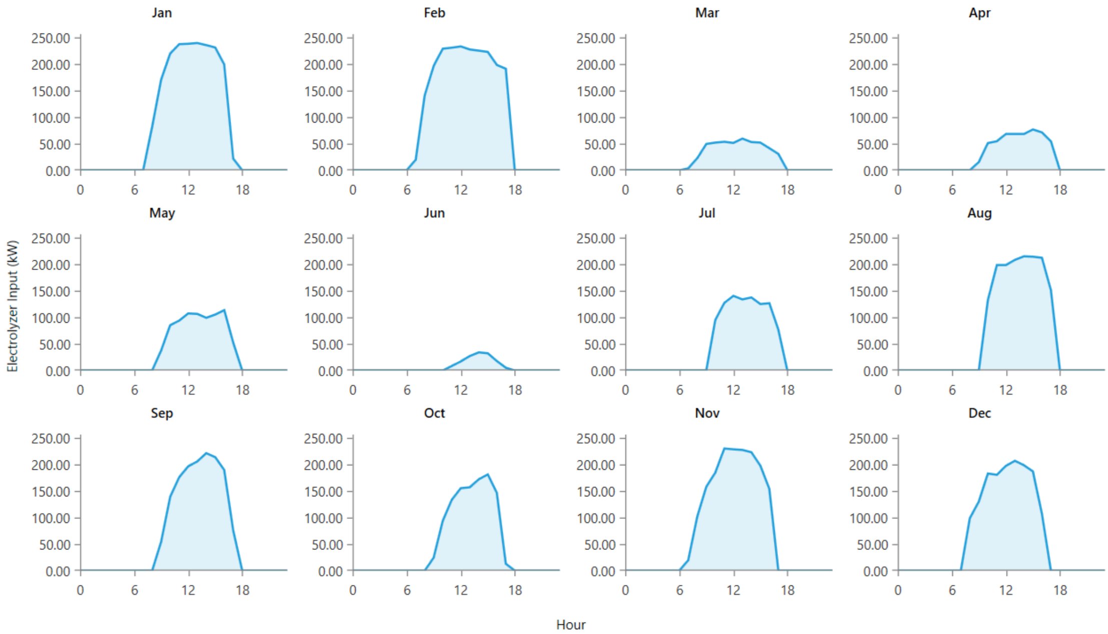

Figure 5.19: Electrolyzer Input Average Daily Profile

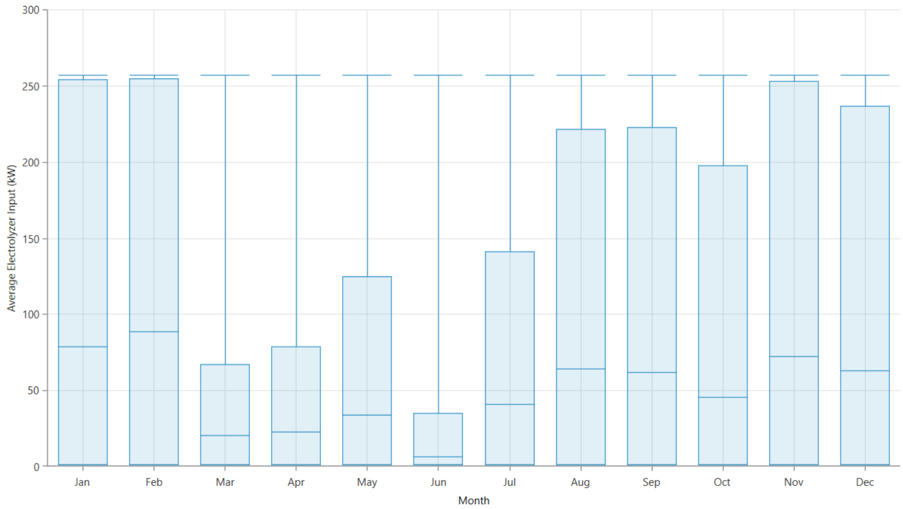

Figure 5.20: Electrolyzer Input Monthly Profile

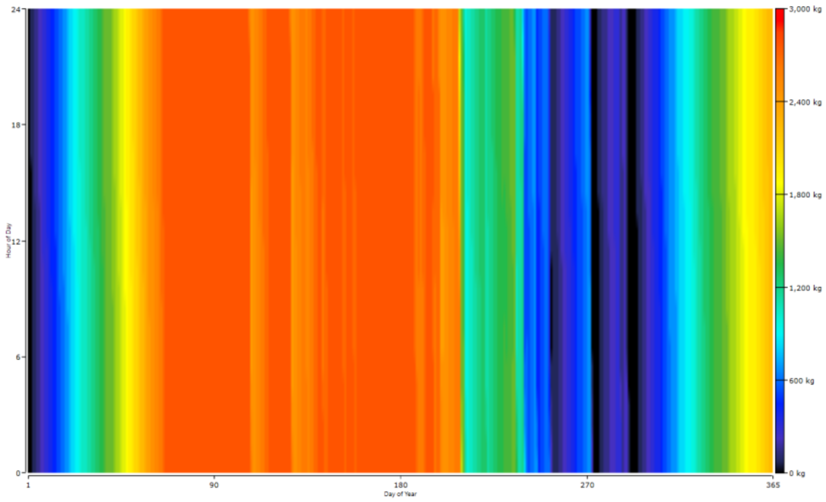

Figure 5.21: DMap Stored Hydrogen

The hydrogen tank's energy storage capacity was 95,000 kWh, providing 614 hours of autonomy. The tank was completely empty at the beginning of the year. Figure 5.21 shows the tank the amount of stored hydrogen in the tank throughout the year. By March, the tank reached full capacity. From March to June, the PV-BESS system appeared to cover most of the load demand, which kept the tank's hydrogen level at its maximum (as also indicated in Figure 5.22), with only occasional drops when the fuel cell needed to operate. However, the tank's hydrogen level dropped significantly from August to November and was unable to fully recover during those months.

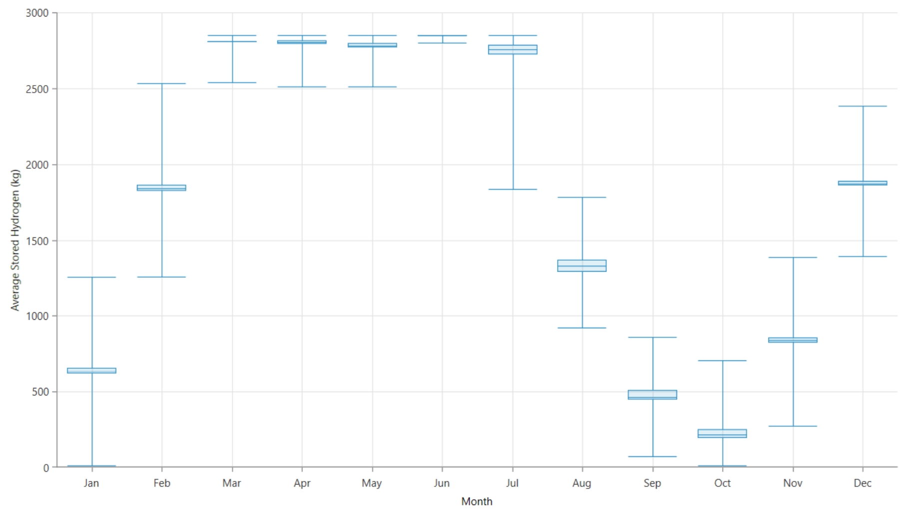

Figure 5.22: Stored Hydrogen Monthly Averages

An unmet electric load of 945 kWh is detected on October 5th, as shown in Figure 5.23.

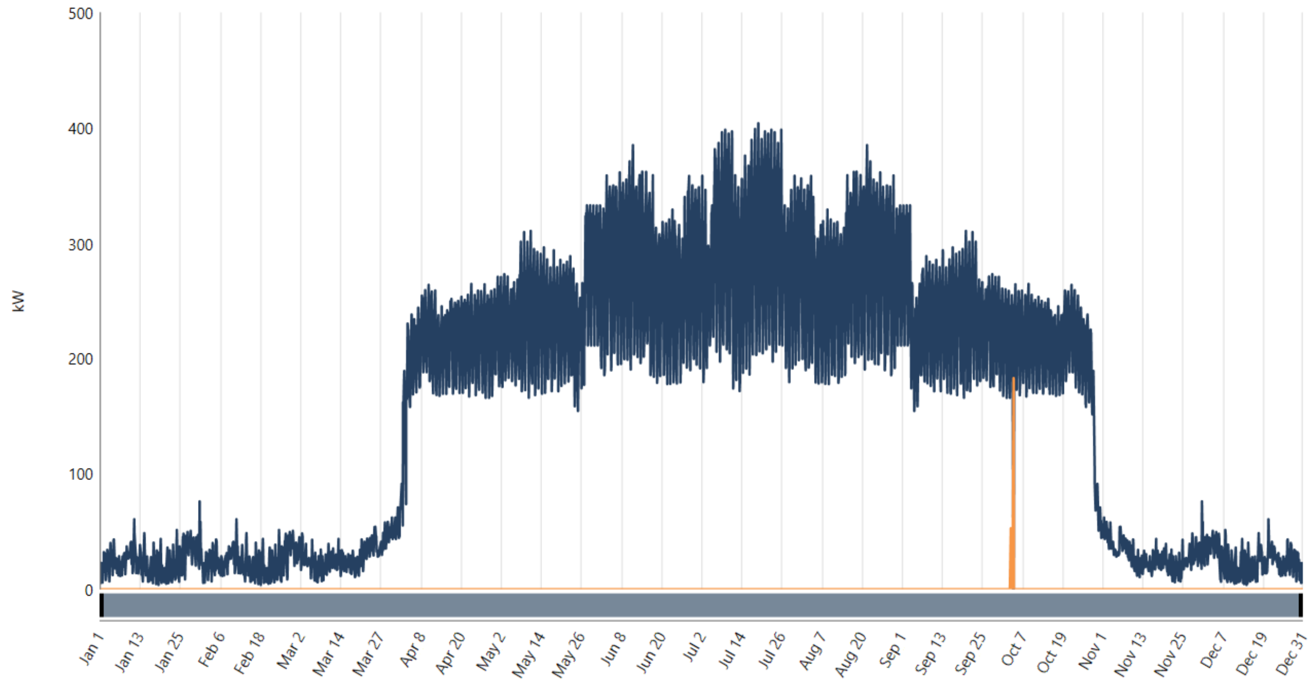

Figure 5.23: Unmet load compared to AC Primary Load Served

Figure 5.24 illustrates the system operation of the PV, BESS, P2H2P system in scenario S.3 during the year, while Figure 5.25 for one week in a typical solar radiation summer month of July. The plot demonstrates the contribution of the PV production in covering the load demand, while also showing the BESS contribution on covering the hours where generation is not possible. Figure 5.26 illustrates the system operation for scenario 1 for one week in a lower solar radiation winter month of January.

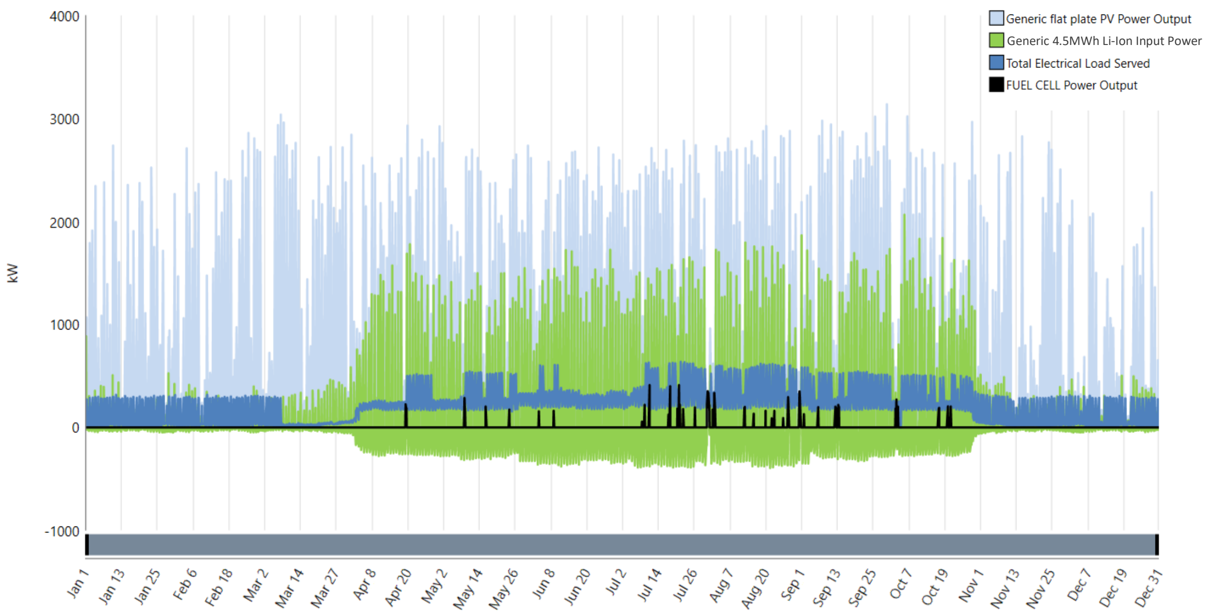

Figure 5.24: Annual load, PV production, BESS, FC profile

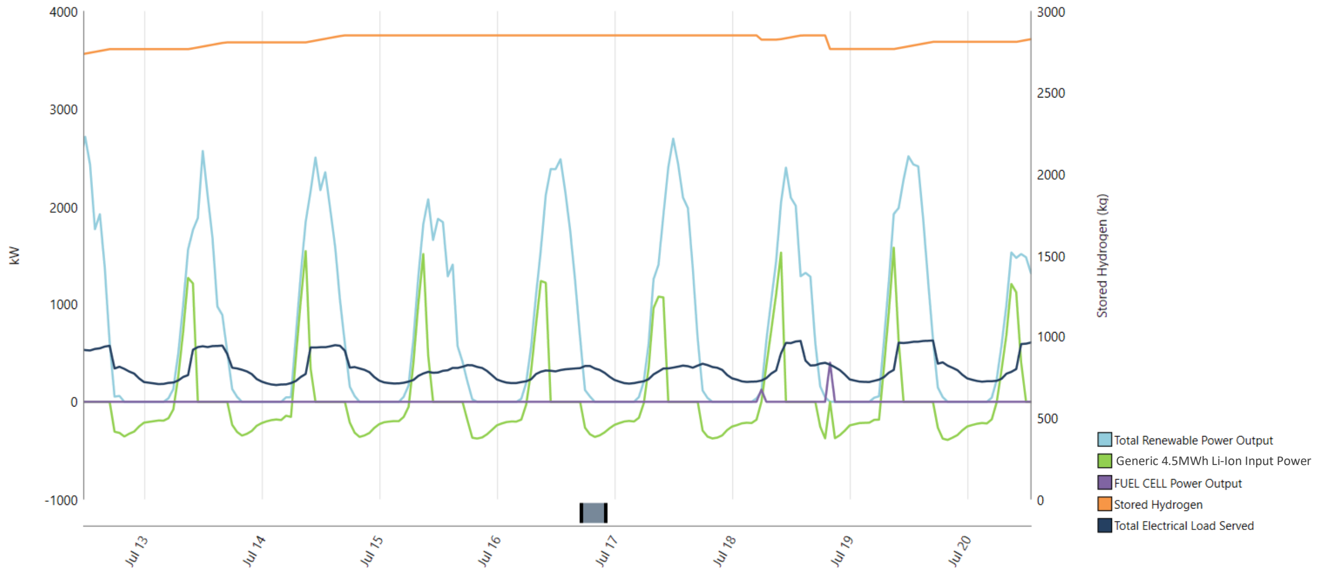

Figure 5.25: One week load, PV production, BESS, FC profile (July)

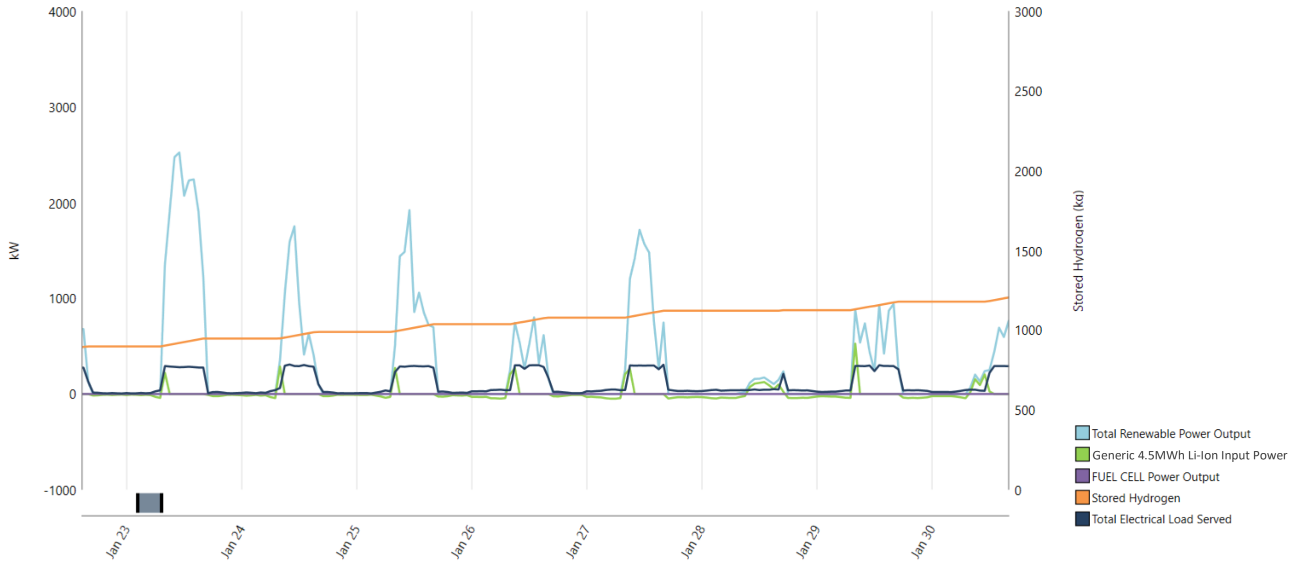

Figure 5.26: One week load, PV production, BESS, FC profile (January)

The total NPC for scenario S.3 is 15.6 million euros. The allocation of funds spent during the project's lifetime are shown in Figure 5.27. The system's initial CAPEX is 13.6 million euros and annualized System O&M cost is 187,310 €/year, while the LCOE in this case is estimated to be 0.88 €/kWh during the project's lifetime (25 years). The system does not appear any emission harmful for the environment.

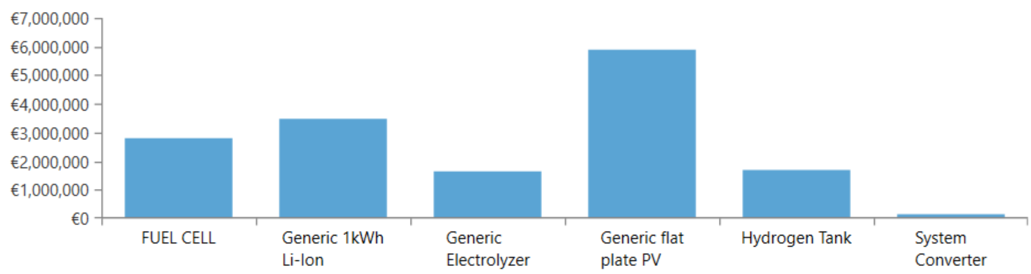

Figure 5.27: Scenario S.3 - NPC

5.3 Comparison of Results for Scenarios S.1, S.2, S.3

Table 5.3 shows the simulation results for scenarios S.1, S.2 and S.3 based on inputs analyzed in Chapter 4.

Scenario S.2 was not a feasible solution for this case study, indicating that under high and seasonal load demand a microgrid cannot operate either technically or financially without a BESS. This result is explained due to the low efficiency and high cost of the P2H2P systems. The unique load profile, characterized by continuous high electricity consumption for 24 hours over seven months of the year, renders the P2H2P system impractical as a standalone solution. Its low efficiency and high cost confirm that while the P2H2P systems are suitable for seasonal storage, they are not effective for daily energy storage.

Between S.1 and S.3 the scenario with the lowest NPC was S.1 by 2.4 million euros, while also having the lowest LCOE by 0.127 €/kWh, evaluated over the project's lifetime. Both scenarios have zero emissions.

Table 5.3: Comparison of Results S.1, S.2, S.3

Results		**S.1** **Solar PV (10° slope) and BESS**	**S.2** **Solar PV and P2H2P system** (electrolyzer, Fuel Cell, H2 tank)	**S.3** **Solar PV (40° slope), BESS and P2H2P system** (electrolyzer, Fuel Cell, H2 tank)
System Components	Generic flat plate PV (MW)	3.52	Unfeasible	3.161
	Li-Ion BESS (MWh)	9.0	Unfeasible	4.5
	Fuel Cell (kW)	X	Unfeasible	900
	Electrolyzer (kW)	X	Unfeasible	257
	Hydrogen tank (kg)	X	Unfeasible	2,850
	Converter (kW)	439	Unfeasible	474
Electrical values	Total consumption (kWh/year)	1,356,066	Unfeasible	1,800,000
	Excess Electricity (kWh/year)	3,000,000	Unfeasible	2,322,032
	Unmet Electric Load (kWh/year)	1,388	Unfeasible	945
	Unmet Electric Load (%)	0.102	Unfeasible	0.06
	Capacity Shortage (kWh/year)	1,613	Unfeasible	1,120
	Capacity Shortage (%)	0.119	Unfeasible	0.0826
	Renewable Fraction (%)	100	Unfeasible	100
Generic flat plate PV	Generic flat plate PV production (kWh/year)	4,518,133	Unfeasible	4,219,651
Li-Ion BESS	Autonomy (hours)	49.7	Unfeasible	23.9
	Usable Nominal Capacity (MWh)	7.686	Unfeasible	3.7

Fuel Cell	Fuel Cell production (kWh/year)	X	Unfeasible	32,849
	Hours of Operation (hours)	X	Unfeasible	165
	Number of Starts (starts/year)	X	Unfeasible	40
	Fuel consumption (kg)	X	Unfeasible	6,900
Electrolyzer	Electrolyzer consumption (input energy) (kWh/year)	X	Unfeasible	430,754
	Total production (kg/year)	X	Unfeasible	9,282
Hydrogen tank	Energy storage capacity (kWh)	X	Unfeasible	95,000
	Tank autonomy (hours)	X	Unfeasible	614
Emissions	Carbon Dioxide produced (kg/year)	0	Unfeasible	0
	Sulfur Dioxide produced (kg/year)	0	Unfeasible	0
	Nitrogen Oxides produced (kg/year)	0	Unfeasible	0
Finance values	Total Net Present Cost (Total NPC) (million €)	13.2	Unfeasible	15.6
	System initial capital cost (CAPEX) (million €)	10.8	Unfeasible	13.6
	Annualized System O&M cost (OPEX) (€/year)	180,555	Unfeasible	187,310
	Levelized Cost of Energy (LCOE) (€/kWh)	0.753	Unfeasible	0.88

In scenario S.3, despite the reduction in solar PV capacity and a 50% decrease in BESS, the addition of the P2H2P system resulted in a slightly higher OPEX and CAPEX compared to scenario S.1. Meanwhile, scenario S.1 shows an excess of 66.8% electricity produced every year, while in scenario S.3 this percentage comes down to 50% annually. Scenario S.3 covered 99.94% of the total load demand, while S.1 managed to cover 99.89%.

The slope of the panels appears to have a notable impact on the NPC of the scenarios. In scenario S.1, a panel slope of 10º resulted in the lowest NPC, whereas in scenario S.3 the optimal slope was 40º. Given the seasonal load profile with peak demand in the summer, the PV system in scenario S.1 is not required to generate significant energy amounts during the winter months, so a steep panel angle is unnecessary. This adjustment not only reduces the excess energy production, but also addresses aesthetic concerns, as the panels need be mostly installed on top of the resort buildings, and a steeper angle would be visually unappealing to the guests. On the other hand, in scenario S.3, the P2H2P system requires energy production even during winter to store hydrogen for summer use, which explains the need for a steeper panel angle in this case.

Since the goal is to find the most financially feasible solution, scenario S.1 seems to be the winning scenario due to its lowest NPC and LCOE.

In Chapter 5.4, the winning scenario of the 100% RE SAMs, scenario S.1, is financially compared to scenario S.4. In Chapter 5.5, a sensitivity analysis is performed to assess the impact of varying maximum annual capacity shortage percentages and panel slopes on component sizing, NPC and LCOE.

5.4 Results for Scenario S.4 & financial comparison with the winning 100% RE scenario

Scenario S.4 represents a grid-connected AC system. Multiple simulations were conducted to determine the conditions where the LCOE for the S.4 system exceeds that of the winning scenario among systems S.1, S.2, and S.3.
Since system S.1 was the most cost-effective 100% RE SAM, the simulations for S.4 involved adjusting the initial capital cost (CAPEX) in increments of 100,000 euros. The goal was to identify the CAPEX for grid interconnection that would make the 100% RE SAM (S.1) more financially viable. The simulations stopped when the LCOE of S.4 exceeded the LCOE of S.1, which is 0.753 €/kWh.

Table 5.4 shows the results of S.4 where the LCOE exceeded 0.753 €/kWh.

Table 5.4: Optimization Results S.4

	Optimization Results S.4 (Grid-connection)		
Electrical values (Grid)	Grid Purchases	kWh/year	1,356,066
	Excess Electricity	kWh/year	0
	Unmet Electric Load	kWh/year	0
	Energy Sold	kWh/year	0
Emissions	Carbon Dioxide produced	kg/year	857,033
	Sulfur Dioxide produced	kg/year	3,716
	Nitrogen Oxides produced	kg/year	1,817
Finance values	Total Net Present Cost (Total NPC)	million €	13.3
	System initial capital cost (CAPEX)	million €	9.7
	Annualized System O&M cost (OPEX)	€/year	277,322
	Energy Charge	€/year	204,011
	Levelized Cost of Energy (LCOE)	€/kWh	0.758

No PV, BESS or P2H2P systems were added in scenario S.4, thus selling back electricity to the grid is not available. Figure 5.28 shows the annual electricity purchased from the grid, which is equivalent to the load demand, 1,356,066 kWh/year.

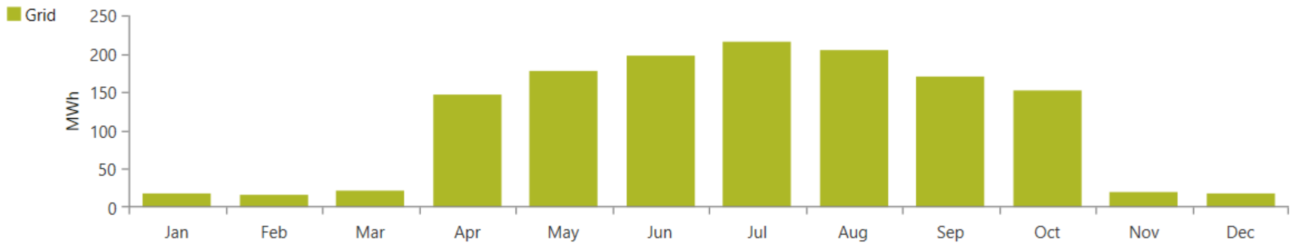

Figure 5.28: Monthly grid purchases

Including the penalties from the emissions, the total NPC in S.4 is 13.3 million euros, system initial capital cost (CAPEX) is 9.7 million euros and LCOE was 0.758 €/kWh (Figure 5.29).

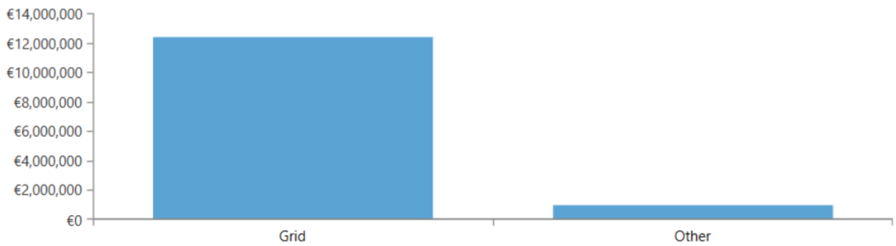

Figure 5.29: Scenario S.4 - NPC

Table 5.5 shows the comparison between the optimization results of scenario S.1 and S.4.

Table 5.5: Comparison of Results S.1, S.4

Optimization Results		
	S.1 (Solar PV and BESS)	**S.4** (Grid-connection)
Total Net Present Cost (Total NPC) (million €)	13.2	13.3
System initial capital cost (CAPEX) (million €)	10.8	9.7
Levelized Cost of Energy (LCOE) (€/kWh)	0.753	0.758
Annualized System O&M cost (€/year)	180,555	277,322

CAPEX represents the initial capital cost, which, in scenario S.4, corresponds to the interconnection cost requested. Simulations in HOMER Pro revealed that when the CAPEX (interconnection and medium to low voltage transformers) equals to 9.7 million euros, the LCOE (€/kWh) becomes 0.005€ higher than that of scenario S.1, even though the CAPEX in S.1 is 1.1 million euros higher than in S.4. This discrepancy can be attributed to the fact that the annualized operation and maintenance costs, are more favorable, almost by 65%, in scenario S.1.

5.5 Sensitivity Analysis for 100% RE SAM winning scenario

Sensitivity analysis is a financial modeling technique used to assess how changes in input variables impact the results of the simulations.

Two multidimensional sensitivity analysis were conducted in this study, to analyze the influence of panel slope and capacity shortage in the NPC and LCOE.

Figure 5.30 and Figure 5.31 illustrate the two-dimensional sensitivity analysis of scenario S.1, showing the impact of two key variables, the PV slope and capacity shortage on the NPC and LCOE respectively of the system. The x-axis represents the capacity shortage percentage ranging from 0.02% to 5%, while the y-axis shows the PV slope in degrees ranging from 10° to 40°. In Figure 5.30, the different colors represent the value of NPC with the red and yellow colors denoting costs up to 16,000,000 € and blue representing lower costs, around 6,000,000 €, while in Figure 5.31 the different colors represent the value of LCOE with red color being the highest value at 0.9 €/kWh, while blue is the lowest value at 0.4 €/kWh.

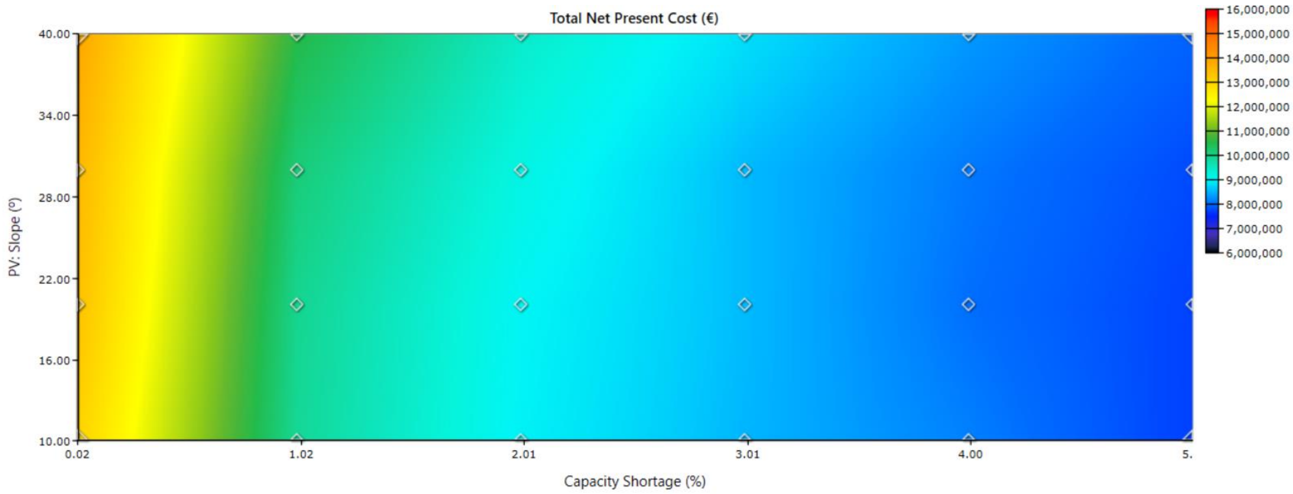

Figure 5.30: Sensitivity analysis – NPC

In both figures, it is observed that as capacity shortage increases, the Total NPC and LCOE decreases significantly showing that allowing more unmet load demand leads to lower NPC and LCOE. The PV slope has a smaller influence on Total NPC and LCOE compared to capacity shortage. However, in low-capacity shortages, such as the one used in the simulations (Chapter 4.5), adjustments to the PV slope do impact the Total NPC and LCOE. As illustrated in Figure 5.30, at a capacity shortage 0.02% the Total NPC ranges from 15 million euros to 13 million euros as the PV slope varies from 40° to 10° respectively. As capacity shortage increases, the PV slope does not significantly affect the Total NPC. A similar pattern is observed in LCOE in Figure 5.31.

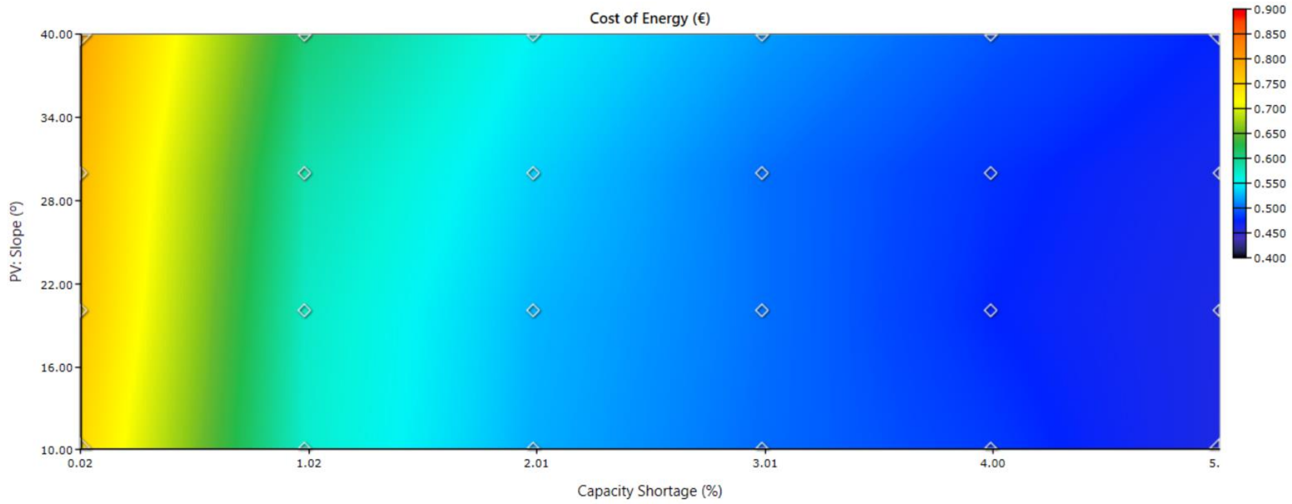

Figure 5.31: Sensitivity analysis - LCOE

Figure 5.32 illustrates the total electrical load served versus the unmet electrical load of the sensitivity analysis with 2% capacity shortage and 10° PV panel slope. In this case the NPC is estimated at 9 million euros with LCOE of 0.525 €/kWh.

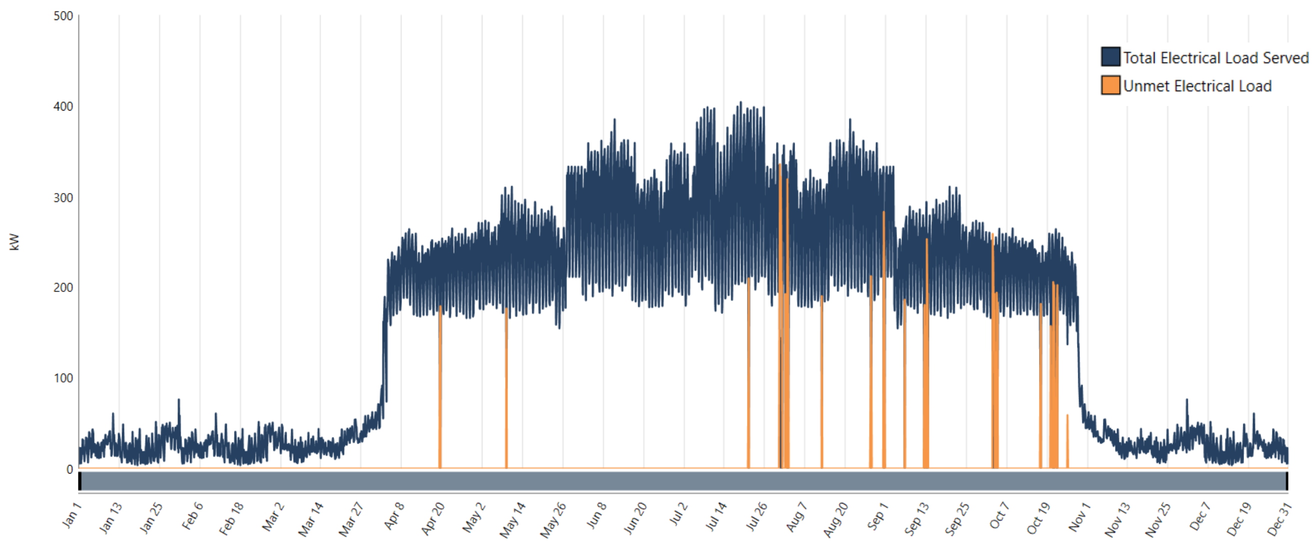

Figure 5.32: Sensitivity analysis (2% capacity shortage, 10° PV slope) – Load Served, Unmet load

As expected, there are more instances throughout the year where the system is unable to fully meet the resort's energy demands. However, measures can be taken to maintain this case while ensuring guest comfort. One approach would be to prioritize loads into essential needs, which must always be fulfilled, and secondary needs, which can be curtailed when electricity is insufficient. For instance, secondary loads might include the cooling system for the reception building or the heating for swimming pools. Reducing these secondary loads would significantly decrease the total unmet load while also lowering the NPC and LOCE, especially in comparison to those in scenario S.1.

5.6 Discussion of the Results

Based on the input data and the constraints given to HOMER Pro, the software optimally sized in scenarios S.1, S.2 and S.3 components that could form a remote microgrid of a resort with seasonal load of 1,356,066 kWh/year. During the simulations, solar PV system, BESS and the converter were optimized by the software, while for electrolyzer's, fuel cell's and hydrogen tank's size, the software selected the optimal size from the predefined list of available sizes. In addition to managing short-duration peak loads, the BESS was also utilized for ancillary services, such as frequency regulation and voltage control within the microgrid. All simulations were made to find the most feasible technical solution with the lowest NPC.

Scenario S.2 provided valuable insights, revealing that even in systems with seasonal operation, each load has unique requirements. In this case, due to the high 24-hour load demand during seven months of the year, incorporating a BESS in the SAM is essential for optimal performance. Scenario S.3 demonstrated that while P2H2P systems offer a promising solution for achieving microgrid autonomy in remote areas, there are still significant techno-economic challenges to address.

The lowest NPC between scenarios S.1, S.2 and S.3 appeared to be the one of S.1 despite the larger solar PV system and BESS. The CAPEX and OPEX of S.1 were lower than those of scenario S.3. The LCOE in scenario S.1 was 0.127 €/kWh lower than scenario S.3. Meanwhile, by conducting a sensitivity analysis, the slope of the panels appears to have a notable impact on the NPC and LCOE of the scenarios S.1 and S.3.

Scenario S.4 provided the lowest interconnection CAPEX for linking a remote area to the grid, beyond which the LCOE would surpass that of the 100% RE SAM winning scenario, scenario S.1. This CAPEX is influenced by the distance between the remote microgrid and the nearest high-to-medium voltage transformer. The CAPEX for Scenario S.4 was determined to be 9.7 million euros. Considering the additional costs for a medium-to-low voltage transformer, the Power Transmission Operator would need to charge approximately 8.9 million euros or more for the 100% RE system to be the most financially viable option. As a result, it is likely that in some locations the S.1 solution would be more economically feasible than grid connection.

The two-dimensional sensitivity analysis explored the effect of the PV panel slope and capacity shortage on NPC and LCOE. Results showed that as capacity shortage increases, both NPC and LCOE decrease significantly, with capacity shortage having a greater impact that the PV slope. Thus, a suggested strategy to reduce unmet loads involves prioritizing essential energy needs over secondary ones, such as cooling and heating for non-crucial areas in the resort.

Chapter 6: Conclusion

The primary objective of this thesis was to explore the techno-economic feasibility of a 100% renewable energy stand-alone microgrid for a resort located on a remote island in northern Greece. The study focused on addressing the seasonal and daily fluctuations in energy demand by investigating various configurations of PV, BESS and P2H2P systems. Based on simulations conducted using HOMER Pro software, the following key results were obtained:

- The analysis of the three 100% RE scenarios indicated that the PV-BESS combination (scenario S.1) is the most viable solution for the stand-alone microgrid of this resort.

- A P2H2P system consisting solely of a PV, electrolyzer, FC and hydrogen tank, without a BESS, is not an economically feasible solution for the type of load in this project, due to the high cost but low efficiency of the system.

- The hybrid system (scenario S.3) results in reduced amounts of excess generated electricity compared to the PV – BESS systems (scenario S.1), while providing lower capacity shortage.

- When the CAPEX for the interconnection and medium to low voltage transformers surpasses 9.7 million euros, creating a stand-alone microgrid is the most financially feasible solution.

The two unexpected but valuable findings were that the P2H2P system, without the inclusion of a BESS, is not always a technically or economically viable solution due to its low efficiency and high costs. Therefore, there are still significant techno-economic challenges to overcome in this scenario to meet a resort's energy demand of a standalone microgrid. Additionally, there are likely many instances globally where a remote resort like the one in this study could financially benefit more from a stand-alone microgrid than from connecting to the grid.

The first hypothesis suggested that by optimizing the sizing of microgrid's components, a 100% RE stand-alone microgrid could be both technically and economically viable solution for the project. The results confirmed this hypothesis, showing that the PV – BESS configuration (scenario S.1) offered the most cost-effective solution achieving the lowest NPC while reliably meeting the resort's annual energy needs.

The second hypothesis proposed that while incorporating a P2H2P system would result in higher NPC compared to the configuration without it, it would provide a more reliable energy supply. This hypothesis was also validated by the results. The scenario S.3 did indeed show higher costs due to the added complexity and components, but it also offered enhanced reliability.

In addition to the insights gained from this study, there are several opportunities for future research. While this thesis focused on a stand-alone PV, BESS, P2H2P system configuration, due to location's limitations, future work could explore the integration of additional renewable energy sources. Investigating hybrid systems combining multiple sources could provide further optimization of both NPC and performance. Furthermore, another scenario worth exploring is a grid – connected system that incorporates RES. Since the current results show that nearly half of the energy produced is not utilized, this scenario could involve selling the excess electricity back to the grid, potentially providing financial benefits. The NPC and LCOE of this setup should be analyzed to determine if it is a viable and worthwhile option. In addition, future research could explore strategies for reducing unmet loads by prioritizing essential energy needs over secondary. Finally, the model presented in this thesis could be applied to other remote locations with varying seasonal demand patterns, providing valuable insights into the adaptability and scalability of 100% RE microgrid systems in different contexts.

Supporting Documents and Files

This section outlines the key documents and files that were either used as references or generated during this thesis. These materials provide supplementary insights and support the findings and methodologies presented in the main body of work.

The original electricity consumption data from the existing resort, collected during the research, is stored in two Excel files: "DAILY CONSUMPTION" and "DATA_AND_PROCESSING". The "DAILY CONSUMPTION" file contains the resort's daily electricity demand, while the "DATA_AND_PROCESSING" file records the hourly electricity demand. Both files also include the necessary conversions and calculations used to transition from the current resort setup to the case-study resort model. The "HOMER INPUTS" file contains 8,760 values, each representing the resort's energy demand load for every hour of the year. These values were used as input data for the HOMER Pro software to model the resort's energy consumption patterns.

Four simulation files were created to model the scenarios described in the thesis: “S.1_PV_BESS”, “S.2_PV_H2”, “S.3_PV_H2_BESS”, and “S.4_GRID”. Each file simulates a distinct energy system configuration, examining the use of PV panels, BESS, P2H2P systems, and grid dependence, to evaluate the performance and feasibility of different energy solutions for the resort’s SAM.

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