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Techno-Economic Feasibility and Environmental Assessment of Multi-Energy Storage Hybrid Systems for EV Charging Solution in the Arctic Region

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ABSTRACT :

This research intends to promote the adoption of EVs in the Arctic regions, particularly in Finland, and reduce the dependency on fossil fuels by deploying off-grid renewable energy integrated charging solutions with multi-energy and storage hybrid systems (MESHS). The study assessed techno-economic feasibility and environmental impact by exploring various energy stakeholders’ opinions on several aspects, like costs and economic aspects, technical feasibility, environmental emission, policy, and social aspects, through a survey. The study also optimized two distinct multi-energy and storage hybrid systems (MESHS), one utilizing hydrogen (H_2) storage and the other using lithium-ion battery storage, by employing the widely used energy simulation software HOMER Pro in a case study.

The H_2-storage-based MESHS included PV, WT, a diesel genset, a converter, an electrolyzer, a hydrogen storage tank, a fuel cell, and a controller (LF), while the lithium-ion battery-based MESHS integrated WT, PV, a diesel genset, a lithium-ion battery, a converter, and a controller (LF). The key performance parameters were the LCC (total NPC), LCOE, CAPEX, OPEX, and emission measurement (CO_2). The models utilize a high number of renewables and result in no unmet load or capacity shortages, making them highly reliable. A sensitivity analysis with various diesel prices was conducted, and the impact on the variable changes was observed. The proposed MESHS models individually highlighted lower costs and minimal environmental impact compared to a conventional diesel-based energy system, but they demand higher capital expenses, which challenged the faster establishment of the charging infrastructure. When comparing the two optimized MESHS, the results indicated that the H_2-storage model outperformed the lithium-ion battery system by demonstrating lower LCC (total NPC), LCOE, and OPEX. Furthermore, H_2-based MESHS reduced significant GHG emissions, including CO_2, and saved more diesel consumption than lithium-ion battery-based MESHS. However, CAPEX for the lithium-ion storage is less than that of the H_2-based storage model. Additionally, H_2-based MESHS resulted in higher IRR and faster payback, which indicated high profitability with H_2 storage. With the H_2-storage model, there are possibilities to utilize the excess electricity through an electrolysis process using the electrolyzer, and it could be stored in the storage tank or fuel cell or serve an external purpose, which offers additional financial benefits with H_2-based MESHS. Likewise, the H_2 storage tank autonomy is comparatively higher than the lithium-ion battery storage, which is crucial for long-term storage solutions for EV charging stations in the Arctic climate condition.

Overall, the findings present the potential of H_2-based MESHS as a viable charging solution for EVs in the Arctic region. The study conveys valuable insights for the industries in considering potential business investments and policy makers, supporting the deployment of sustainable EV charging infrastructures, hence promoting EV adoption in the Arctic region.

KEYWORDS: EVCS, MESHS, RES, LCC, NPC, LCOE, Emission, Arctic Region

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Abbreviations

CAPEX: Capital Expenses

DOD: Depth of Discharge

EV: Electric Vehicle

EVCS: Electric Vehicle Charging Station

GHI: Global Horizontal Irradiance

Gen100 (D): Diesel Generator (100kW)

HTank: Hydrogen Storage Tank

IRR: Internal Rate of Return

kWh: Kilowatt-hour(s)

kW Kilowatt(s)

LCC: Life Cycle Cost

LCOE: Levelized Cost of Energy

LCOH: Levelized Cost of Hydrogen

LCOS: Levelized Cost of Storage

MESHS: Multi-Energy Storage Hybrid Systems

NPC: Net Present Cost

NREL: National Renewable Energy Laboratory

O & M: Operation and Maintenance Costs

OPEX: Operation Expenses

PV: Photovoltaic

RF: Renewable Fractions

ROI: Return on Investment

RESs: Renewable Energy Sources

SOC: State of Charge

WT: Wind Turbine

1 Introduction

The rising demand for fossil fuels is making prices high and making energy less reliable. Fossil fuel-powered vehicles release large amounts of greenhouse gases (GHG), which affect climate change (Rong et al., 2025). Due to the world's fast-moving approach toward electric vehicles (EVs), it becomes crucial to have more sustainable transportation and less reliance on fossil fuels (Udendhran et al., 2025). Despite the increasing need to reduce carbon emissions, many challenges exist in adopting electric vehicles across various regions of the world. One significant constraint is the availability and accessibility of electric vehicle charging infrastructure (Udendhran et al., 2025, p. 1). The need for public charging points depends on where drivers are and how they act. More public charging stations in the EU can support people with EV adoption (IEA, 2025, p. 101). To meet the energy demands of EV users and keep up with their changing needs, public electric charging stations are essential (Rong et al., 2024). Clean energy and electric vehicles (EVs) are becoming more popular as an alternative to gas-powered cars. But the lack of long-lasting charging infrastructure is still challenging. The grid, which may still use fossil fuels to power most regular EV charging stations, contributes to pollution. Solar-powered charging stations are a promising solution because they use a lot of renewable solar energy that is beneficial for the environment (Rao et al., 2024, p. 2). Charging stations that use renewable energy could help shared mobility services have less of an environmental impact. However, putting in on-grid charging stations is often challenging because of administrative processes and costs a lot of money, which slows down the growth of e-mobility (Schelte et al., 2021, p. 33). Grid-independent solar charging stations are more flexible. Charging stations can help extend battery life by allowing people to charge their electric vehicles more frequently. This means fewer trips to swap batteries and more people switching to transportation that runs on renewable energy (Rong et al. 2025, p. 837). Relying solely on off-grid solar energy and regular battery storage to charge electric cars is insufficient to eliminate the need for the grid, as sunlight availability varies with the seasons (Rong et al., 2025, p.838). Storage is required for an electrical system with renewables when fossil fuels are replaced. To ensure the reliability of the network, it is then essential to provide backup for the intermittent renewable energy sources. Hydrogen storage systems offer a promising solution for long-term electricity storage (Begum, 2024, p. 3). Limiting renewable energy sources necessitates storing extra electricity to ensure backup power. Batteries are important for stabilizing the supply, but hydrogen electrolyzers are a better option for long-term energy storage because they also make hydrogen. Hybrid EV charging stations that use solar, PV, and biogas reduce a large amount of CO_2 emissions and make energy prices lower. For a sustainable transition, the energy system needs to be both technically and economically stable and have less impact on the environment. Furthermore, to play an important part in decarbonization, it is important to combine renewable sources with a hybrid energy model. Considering the meteorological, financial, and regulatory requirements, it is necessary to conduct region-specific studies that examine environmental impacts, financial feasibility, and technical optimization (Rong et al., 2025, pp. 837-838). The charging priorities outline the situations in which consumers charge their vehicles, as well as the placement of charging stations and charging techniques. These factors should be considered when modelling the charging load (Ahmed and Selveraj, 2022). Stakeholders may evaluate a renewable energy-based charging infrastructure project by examining the ecological and economic aspects. For better risk management and planning, sensitivity analysis and financial modelling can be combined (Sayed et al. 2025, p. 61857).

The Arctic region has unique climate conditions with frigid and dark winters. However, the area is rich in solar power during the summer and wind power all year. The abundance of renewable resources, such as green hydrogen, is also emerging as a potential energy source and storage for vehicle charging. This study attempts to mainly assess the viability and the environmental impact of the multi-energy storage hybrid systems for a grid-independent, renewable energy-powered EV charging infrastructure in the Arctic region, particularly Finland.

1.1 Research Objective and Questions

The primary goal of this study was to investigate techno-economic feasibility as well as the environmental effects of creating off-grid multi-energy storage hybrid systems (MESHS) for electric vehicle charging stations. The assessment emphasizes optimization of the MESHS modeling for off-grid EV charging solutions. The research will consider the unique environmental, social, and economic factors specific to the Arctic remote location. It employs measuring the life cycle cost or total net present costs and levelized cost of energy of the multi-energy storage systems and comparing these with the traditional fossil fuel (particularly diesel) based energy systems to identify the most viable and cost-effective storage system for EV charging solutions. The study measures the environmental emission of renewable energy-based multi-energy storage systems (MESHS) with traditional fossil-fuel-based energy systems. Additionally, the socio-economic concerns and policy factors relevant to the needs and values of the Arctic inhabitants will be briefly explored.

Thus, the study will promote EV adoption in the Arctic region and identify the cost-effective, viable, and sustainable energy storage solutions for EV charging. Ultimately, the study will support limiting the dependency on fossil fuel energy sources, solve the complexity with the grid-connection, and reduce carbon emissions. Moreover, it will assist policymakers to employ regulations, encourage the local community and industry partners to establish charging infrastructure.

To complete this study, the following research questions will be explored,

- How do the total life cycle cost (LCC) and levelized cost of energy (LCOE) of the renewable energy-based MESHS vary with fossil fuel (diesel) - based energy systems in Arctic conditions?
- Which multi-energy storage system (MESHS) results in the most cost-effective and viable model for grid-independent EV charging solutions in the Arctic region?
- How is the environmental impact of the renewable energy-based MESHS for EV charging stations compared with diesel-based systems under Arctic climate conditions?
- How does the performance of different energy storage technologies vary with the extreme Arctic situation when integrated with RESs?
- Which policy measures and social factors may impact adopting MESHS-based EV charging solutions in the Arctic region?

1.2 Limitations

Time constraints restrict extensive literature reviews and the ability to obtain a higher number of survey responses or conduct more sensitivity cases in the simulation process. Additionally, direct interviews with industry experts, researchers, or the local community of the study location were not conducted again due to time constraints and individual workloads.

1.3 Responsibility and Study Environment

This study is part of a master's thesis. The research methodology includes data analysis and evaluation of survey results and simulations. A brief literature review provided secondary data required to understand the research topic, prepare the survey questionnaires using the equations necessary for the system optimization and component cost, and find the research gap. All the tasks were performed in a single effort, including searching and reviewing the literature, preparing the survey questionnaires, and attending the Energy Week 2025 event to meet industry personnel, energy enthusiasts, researchers, and relevant stakeholders to collect contact email addresses for the survey participation. A Microsoft Form link was created for survey questionnaires along with QR code generation. At first, the survey questionnaires were shared with a printed version, which included the QR code and form link, and were shared with the companies, researchers, academics, local energy students who are at the university, and inhabitants in person during the Energy Week event 2025 at Vaasa. Additionally, the survey form link and QR code were sent to the participants by email during and after the energy week event.

Besides, managing HOMER Pro software for the energy simulation and feasibility experiment and further evaluation of the collected information, data analysis, and writing were mostly done by individual students. The locations of the data collection process include both in-person and online from home, the energy event, and the University of Vaasa. The primary support for the entire study period was the supervision of the project supervisor. Additionally, discussing with the energy technology lab colleagues about the simulation results supports the evaluation. Regular supervision was conducted through online meetings using a Zoom sharing link, or in-person, and mostly sharing files or documents by e-mail.

2 Theoretical Framework

2.1 Literature Reviews

In this section, previously done research is explored in areas aligning with this thesis, including hybrid energy storage systems, techno-economic assessment, micro-grid optimization, and social and policy measures relevant to the EV charging infrastructure to get a basic understanding of the subject matter, obtain simulation-relevant technical information, and identify the study gaps.

Oladigbolu et al. (2023) investigated a techno-economic feasibility study on EV charging stations integrating renewable energy sources. The study locations were six different places in in Nigeria considering different climates situation. They employed HOMER Pro software for optimization. Their optimized system combined a PV, wind turbines, and battery storage, systems. The best setup at Sokoto, which had a minimum unmet load of 1.38%, included two wind turbines, 174 kW of solar panels, 380 batteries, and a 109-kW converter. It had the lowest NPC of $547,717 and an energy cost of $0.211/kWh. Through sensitivity study they observed the robustness of the model varying with different technical and economic indicators. Their study highlighted the PV/WT/battery systems as the best solution to charge electric vehicles in Africa. They could also cut down on CO_2 emissions by a lot, even though the high initial prices are still a problem (Oladigbolu et al. 2023).

Through a techno-economic feasibility and environmental assessment, Rong et al. (2025) investigated the cutting-edge hybrid energy system for hydrogen production and electric vehicle (EV) charging in Makkah, Saudi Arabia. They optimized renewable, and reliable, energy sources by integrating grid electricity with photovoltaics (PV), wind turbines (WT), batteries, biogas (BG), and electrolyzers. HOMER Pro 3.14, software was employed to investigate various models and their proposed model that comprised the PV/WT/BG/Grid/Electrolyzer system was the best option. The annual operating costs reached \$18,599, the NPC was \$801,811, and the COE observed \$0.058/kWh. The LCOH resulted in \$4.55 per kilogram. Their optimization model achieved 99.4% renewable energy fraction and 2,687 kg/year of CO_2 emissions. The study confirmed that hybrid systems could provide a viable solution for sustainable EV charging infrastructure.

Barsoum and Petrus (2015) optimized a stand-alone hybrid renewable energy system (HRES) for remote areas where grid connection was not supported. The hybrid system model of their study incorporated solar PV, micro-hydro, a hydrogen fuel cell, diesel backup, batteries, an electrolyzer, and a hydrogen tank. HOMER software was used to optimize the hybrid energy model. They assumed a daily energy demand of approximately 257 kWh and a peak load of 72 kW. Meteorological and load data were collected to simulate various scenarios in HOMER. The performance parameters of their assessment were the NPC, operating cost, LCOE, and emissions of each configuration. Their optimized design comprised 10 kW of PV, 40 kW of micro-hydro, 20 kW of diesel generation, and 5 kW of hydrogen fuel cell capacity. The system resulted in an LCOE of \$0.068/kWh, with an NPC of \$148,902 and an annual operating cost of \$3,794. Their study demonstrated that hybrid renewable systems, particularly those leveraging consistent hydro resources, can effectively power off-grid areas with minimal reliance on fossil fuels. They obtained a large amount of emissions reduction compared to diesel-based systems.

A techno-economic assessment of renewable-powered EV charging stations involving green hydrogen production was conducted by Maghfuri et al. (2025. Through their study they aimed to control excess electricity under various consumption patterns. They emphasized optimizing the COE and ensuring efficient use of excess electricity via a net-zero grid exchange strategy. They utilized multiple EV charging profiles—including midday residential, office-commercial, highway, and public transport. Their study demonstrated that using standard chargers could lower the COE of \$0.042–\$0.061/kWh with over 60% renewable contribution. For fast chargers, COE ranged from \$0.058–\$0.067/kWh, with more than 45% renewable share. Employing electrolyzers, excess renewable power is converted to green hydrogen and increases COE by about 20% but significantly reduces power curtailment, lowering excess electricity from over 30% to under 5%. The levelized

cost of hydrogen (LCOH) ranged from \$3.1 to \$7.2 per kilogram. Their optimized system offered a promising dual-solution for EV and hydrogen-fueled vehicle infrastructure in regions with high solar/wind potential and moderate grid tariffs (Maghfuri et al. 2025).
Youssef et al. (2023) conducted an extensive analysis of an island-type green energy system optimized by photovoltaic, wind, biomass, and battery technologies. The main goal of the project was to make a hybrid renewable energy system that would be the cheapest for an international school in New Cairo, Egypt. They utilized HOMER software to test and compare eight hybrid models that employed varied combinations of energy sources and battery types, like lithium-ion and lead-acid batteries. The results showed that a PV/Wind/Biomass hybrid system with lithium-ion batteries was the best. It had the lowest NPC of \$6.23 million and the lowest LCOE of \$0.382/kWh. The system also only needed two lithium-ion batteries, which are more than ten times fewer batteries than 2,784 lead-acid batteries. This means that the system worked better and was easier to use. The study indicated that lithium-ion battery technology improved the economic viability and performance of off-grid hybrid renewable systems (Youssef et al., 2023).
Haddad and Javani's (2024) examined the application of hybrid renewable energy systems (HRES) in conjunction with battery storage and hydrogen production within energy-efficient buildings. The study employs TRNSYS simulation and a Python-based controller to simulate two building scenarios. The study presented how to keep lithium-ion batteries charged and send extra energy to make green hydrogen when the state of charge (SoC) exceeds 75%. The hybrid energy system was equipped to store hydrogen, solar panels (PV), wind turbines, and a small diesel generator. The results showed that diesel use has limited to 56.14%, which means that CO_2 emissions will go down by 33.86 tons a year. The hybrid system costs needed to fix; however, it saved 96% in the long run. There is also a maximum rate of 15.52 m^3/h at 1.3 bar pressure for making 7582.74 kg of hydrogen each year. The study shows that hybrid systems are cheap and good for the environment to power near zero energy buildings. These systems help cities stay sustainable and energy-resilient over time by using less fossil fuels and releasing fewer greenhouse gases.

Sood et al. (2022) explored the environmental and economic effects of a solar photovoltaic (PV)-based hybrid energy system that was made to power electric vehicle charging stations (EVCS) in urban India. Using HOMER Pro, the authors modeled and optimized a system with solar PV, lead-acid battery storage, and a converter to meet an average daily load of 1065 kWh, which is enough to charge about 30 electric vehicles a day. Four solar load demands were tested i.e. 150 kW, 175 kW, 200 kW, and 216 kW. The 216-kW system had the lowest net present cost (NPC) and levelized cost of energy (LCOE), which meant it would take 7.21 years to pay back. The site was Greater Noida, India and was chosen because it has good solar irradiance and city-level traffic. The system is designed to take up an area like that of a regular gas station (800–1200 m^2). Using SimaPro and Indian LCA standards, a life cycle assessment showed that these systems have a much smaller effect on the environment than grid-powered charging systems (Sood et al., 2022).

Chatterjee and Rayudu (2017) performed a techno-economic evaluation of a hybrid renewable energy system (HRES) designed to deliver dependable, off-grid electrification for a rural household in Sapra, Jharkhand, India. The proposed HRES was made up of a 1 kW solar PV array, a 1 kW wind turbine, a 2.16 kWh battery (Trojan L16P), and a 0.5 kW converter. It was designed to meet a daily energy demand of 4.08 kWh using 100% renewable energy. HOMER simulated the system over a 25-year period using NASA-based solar and wind data. It made 1,563 kWh of electricity from PV and 1,194 kWh from wind each year. It had very little unmet load (0.5 kWh/year) and the battery was always more than 95% charged. The system was economically sound, with an NPC of $4,148, a COE of $0.216/kWh, and an annual operating cost of only $37.73. The system made more electricity than it needed during times of high winds, but it still helped rural areas with energy poverty without using fossil fuels. The research underscored the viability of decentralized renewable solutions in off-grid regions while acknowledging constraints, including the presumption of static battery performance and the neglect of broader community energy requirements (Chatterjee & Rayudu, 2017)

Bilal et al. (2024) examined the electric vehicle charging systems (EVCS) that were combined with renewable energy sources and battery storage systems in four different cities in Saudi Arabia. Their system comprised solar panels, wind turbines, diesel generators, grid connections, and battery storage. They utilized the Improved Salp Swarm Algorithm (ISSA). They also compared the performance of ISSA with the Grey Wolf Optimizer (GWO), Salp Swarm Algorithm (SSA), and Flower Pollination Algorithm (FPA). They also conducted a sensitivity analysis on system performance, using variables such as real solar irradiance, inflation rate, discount rate, and LPSP. The results indicated that the performance with ISSA algorithms was better than the other algorithms. Through a grid-based system, they obtained the lowest LCOE of $0.0711/kWh in Medina with a TNPC of $79,573.71. The proposed model with batteries across all selected cities achieved zero CO_2 emissions, while their proposed system with grid configuration reduced TNPC by $95,692, with operating expenses of $2845.42 and an RF of 67.9% in Riyad. The TNPC was $96,576.59 with an LCOE of $0.1995/kWh. In Jeddah and in Mecca, the TNPC was $93,272.57 and an RF of 56%. The findings resulted in cost reduction, with LCOE reduced from $1.02 to $0.4231 in Riyadh, highlighting the increasing lack of power supply from 0% to 5%. Their study advocated a model for city planners and regulators to promote the deployment of viable and sustainable EV charging infrastructures.

Rao et al. (2024) optimized and investigated a novel solar-powered EV charging station. To provide sustainable energy for charging electric vehicles, the system combines photovoltaic panels with battery storage with effective power management. Even in different weather conditions, their system’s solar energy generation efficiency was 95% and its average charging efficiency was 94.5%. The study emphasized benefits, like grid-powered charging, which costs $362.50 per month, solar charging resulted with no operating costs. A reduction in CO_2 of 1,448 kg per vehicle annually. dependable energy delivery across a variety of EV models, demonstrating the robustness and scalability of the system. The system also showed great flexibility in both urban and rural settings, indicating that future smart grid integration and advancements in battery technology may improve performance and scalability. These results support the idea that solar-powered charging stations should be widely installed as a vital part of the world's green transportation network.

Mastoi et al. (2022) explored issues related to the planning of electric vehicle charging infrastructure. Their review focused on the status of EV adoption, smart grid integration, and optimal charging station location at the present time. However, the research presented valuable insights relating to the various technological improvements regarding the design and development of the charging infrastructure. More specifically, the study emphasized the research and developments on the charging station, the key barriers, and the efforts required to standardize the infrastructure for future development. The barriers affecting the development of EV charging infrastructure include high installation costs, lack of standardization, and possible overload of the grid, especially with respect to peak charging time. The research stressed the importance of integrating renewable energy sources into charging infrastructure. Furthermore, another significant aspect is the advanced smart grid management system using AI - and the development of dynamic pricing models that can be adjusted in real time as electricity demand and supply fluctuate, ensure the balance and efficiency of the grid. Additionally, the variability and unpredictability of renewable sources are highlighted which advocated for effective electricity storage systems to ensure the EVs, and the grid smooth operation when renewable generation cannot correspond with demand. The study pointed out that government policy and incentives include tax exemptions and credits, unit cost reductions, and even access to public parking space. Government incentives, subsidies for the purchase of EVs, and infrastructure investments are the key elements for enhancing market penetration. Financial incentives, as well as regulations could accelerate the adoption of electric vehicles. The study also presented aligned international standards for charging systems: connectors, payment systems, and safety protocols. They suggested integrated urban planning which will make the EV infrastructure more accessible for larger communities and not only selected areas. This would lead to a greater focus on equitable accessibility toward alleviating issues such as range anxiety, rendering EV adoption a more viable prospect for all. The structures they propose for issues such as integrating EVs mostly with the existing grid and on-demand charging station planning offer valuable guidance for researchers, industry experts, and policymakers moving forward (Mastoi et al., 2022, pp. 11504 - 11526).

Alanazi (2023) mentioned about governments incentive for the EV consumers. According to him tax credits or subsidies as well as investment in building a charging infrastructure will promote adopting EVs. Private individuals in the EU member states face administrative challenges and divided incentives while establishing a charging station in their parking space. These barriers should be eliminated by the states (European Union, 2024).
A brief review of the research studied is depicted in the Table. 1

Table 1. A summary of previous studies of hybrid energy storage systems and EV charging

Source	Study Location	Energy Model	Grid Connection	Storage Technology	Optimization Techniques / Tools	Economics Parameter	Emission Measurement	Social and Policy Factors
Barsoum and Petrus (2015)	Malaysia	Hybrid system: PV/micro-hydro/diesel generator/ hydrogen fuel cell/batteries/electrolyzer	Off-grid (remote)	Hydrogen fuel cells and batteries	HOMER Software	TNPC (Life Cycle Cost), LCOE, operating cost.	Not specified	N/A
Oladigbolu et al. (2023)	Nigeria (6 locations)	PV/WT/Battery	Off-grid	Battery energy storage	HOMER Pro	NPC, COE	CO_2 reduction	N/A
Rong et al. (2025)	Makkah, Saudi Arabia	PV/WT/BG/ Grid/Electrolyzer	Grid-connected	Battery /Biogas / Electrolyzer	HOMER Pro 3.14	NPC, COE; LCOH	CO_2 emissions	N/A
Haddad & Javani (2024)	Istanbul, Turkey	PV/WT/Battery/Green Hydrogen/Diesel	Off-grid	Lithium-ion battery & Hydrogen storage	Python Controller and TRNSYS Software	Hybrid mode 96% cheaper; Hydrogen: 7582.74 kg/year	CO_2 reduction	N/A
Bilal et al. (2024)	Riyadh, Jeddah, Mecca, Medina	SPV/WT/BESS/Grid/DG	Grid-integrated	Battery Energy Storage Systems (BESS)	Improved Salp Swarm Algorithm (ISSA)	TNPC, LCOE	CO_2 emissions	N/A
Magfuri et al. (2025)	West Asia	PV/WT/Battery storage/electrolyzer	Grid-Connected	Battery and Green Hydrogen via electrolyzer	HOMER Grid and MATLAB	COE, LCOH	Not specified	Hydrogen sales
Chatterjee and Rayudu (2017)	Sapra, Jharkhand, India	PV /wind /battery /converter	Off-grid	Lead-acid battery	HOMER Soft	NPC, COE, OPEX (Annual operating cost)	100% HRES; no fossil fuel use, Proposing LCA	N/A

Source	Study Location	Energy Model	Grid Connection	Storage Technology	Optimization Techniques / Tools	Economics Parameter	Emission Measurement	Social and Policy Factors
Barsoum and Petrus (2015)	Malaysia	Hybrid system: PV/micro-hydro/diesel generator/ hydrogen fuel cell/batteries/electrolyzer	Off-grid (remote)	Hydrogen fuel cells and batteries	HOMER Software	TNPC (Life Cycle Cost), LCOE, operating cost.	Not specified	N/A
Mastoi et al. (2022)	Global	Both grid-connected and off-grid EV charging with RESs	Both grid-connected and off-grid	Battery storage for grid stability and hydrogen fuel possibility	N/A	Highlighted high installation cost & dynamic pricing, proposing optimization	Not specified	Tax credits, subsidies, public parking access, access via urban planning, and standardization (connector, safety)
Alanazi, F (2023)	Global	N/A	N/A	N/A	N/A	N/A	N/A	Tax credits, subsidies, and investment
Rao et al. (2024)	India	Solar-powered EVCS	Off-grid	Battery energy storage	Prototype Evaluation	OPEX	CO_2 reduction	N/A
Sood et al. (2022)	Greater Noida, India	solar PV /lead-acid battery/ converter	Grid-connected	Lead-acid battery storage	HOMER Pro for energy simulation SimaPro for LCA	NPC. COE, & Payback Period	SimaPro and Indian LCA standards; lower impact than grid-based EV charging	N/A
Youssef et al. (2023)	New Cairo, Egypt	PV/Wind/Biomass	Off-grid	Lithium-ion vs. Lead-acid batteries	HOMER Software	NPC, LCOE	N/A	N/A

2.2 Research Gap

Several existing studies are available on hybrid energy system-based grid-independent or grid-connected electric vehicle (EV) charging infrastructure in various locations around the world. However, minimal research exists about hybrid energy storage solutions for off-grid electric vehicles' charging systems employing renewable sources, particularly in the Nordic Arctic regions. Furthermore, most of the previous research on this topic has not presented expert or stakeholders’ opinions. Also, socio-economic and policy measures regarding off-grid hybrid energy storage-based EV charging systems have not been explored by the stakeholders. This thesis aims to collect data from energy engineers, researchers, academics, policy makers, business investors, management personnel, residents with energy enthusiasm, and other energy-related stakeholders' opinion on the various aspects, including cost factors, technical and economic feasibility, environmental impact and the social and policy measures through a quantitative survey, and conduct a simulation-based case study focused on the technical and economic feasibility, and environmental emission measurement.

2.3 Key Technological Terms and Definition

Life Cycle Cost (LCC)

The life-cycle cost is the sum of all operating and financing costs and annual electrical energy generation throughout the system’s life, which is computed based on capacity factors of power production (Hunter et al., 2021, p. 2095). A component's net present cost, also known as the life-cycle cost, is the present value of all expenditures associated with installing and operating the component during the project's lifespan, minus the present value of any revenues earned during that period. HOMER Energy (n.d.-a) calculates the present net cost of the system as a whole and each of its components as total net present cost. A system's total net present cost (NPC) includes costs associated with capital, replacement, operation and maintenance, fuel, emissions charges, and purchasing electricity from the grid. Revenues include grid sales income and salvage value. The HOMER software adds cumulative discounted cash flows for each year of the project's existence to determine the overall NPC. HOMER's key economic parameter is the total NPC. Therefore, the total NPC is also denoted as the life cycle cost (LCC). It is also used to rank all system configurations in the optimization findings and determine the levelized and total cost of energy per year (HOMER Energy., n.d.-b).

Levelized cost of energy (LCOE)

The net present value of all finance, operating, tax, and capital costs divided by the system lifetime power sales is the levelized cost of energy. In addition to the variation in the cost of energy input, LCOE takes into consideration the operational distinctions between energy storage and power generation systems, such as possible degradation and self-discharge; energy storage systems need charging electricity, while flexible generation technologies need fuel. Thus, levelized cost of energy (LCOE) makes it possible to compare all technologies consistently, irrespective of whether they use chemical fuel or store mechanical, thermal, or electrochemical energy (Hunter et al., 2021, p. 2081).

The levelized cost of energy (LCOE) is calculated using the formula in equation (1) (Luna-Rubio et al, 2011; Youssef et al., 2023, p.7)

$$\mathrm{LCOE} = \frac{CRFxNPC}{\mathrm{E_{Load}}} \tag{1}$$

Here, $\mathrm{E_{Load}}$ defines the total served electrical load in kWh/year, NPC is the total life cycle cost, CRF is the capital recovery factor. The capital recovery factor (CRF) can be measured with equation (2) (Alam and Bhattacharyya, 2016; Youssef et al., 2023, p.7)

$$\mathrm{CRF} = \frac{(\,r(1+r)^{Y})}{(1+r)^{Y}-1} \tag{2}$$

In eqn. (2) the interest rate per year is depicted as r and the lifespan of the project is Y in years. The interest rate per year (r) can be calculated with the formula (3) (Mandal et al, 2018; Youssef et al., 2023, p.7)

$$\mathrm{r} = \frac{\mathrm{r}' - f}{1+f} \tag{3}$$

Here, r' denotes the nominal interest rate (%) and f presents the yearly inflation rate (%).

Salvage Value

Salvage value is the amount that remains in a power system component at the end of the project's lifespan. The salvage value of an element is precisely proportionate to its remaining life since HOMER assumes linear degradation of components. It additionally assumes that the value of salvage is based on the replacement cost instead of the initial cost of investment and adds prorated maintenance expenses from the last event to the project's completion (HOMER Energy., n.d.-c).

Capacity Factor

A power generator's capacity factor according to Hunter et al. (2021) is the amount of energy it generates over the year round in comparison to the maximum amount of energy it could hypothetically produce if it worked at full power all year long. Likewise the power generator, the capacity factor for recharging equipment is the equipment's yearly energy consumption divided by the maximum energy consumption that the equipment might have if it operated at full capacity year-round (Hunter et al., 2021, p. 2091).

The Renewable Fraction (RF)

The renewable fraction or Ren. Frac (RF) is the percentage of the energy delivered to the load that is generated from renewable power sources. The renewable fraction can be calculated using the following equation (4) (HOMER Pro, n.d.-d).

$$\mathrm{f_{ren}} = 1 - \frac{\mathrm{E_{nonren}} + \mathrm{H_{nonren}}}{\mathrm{E_{served}} + \mathrm{H_{served}}} \qquad (4)$$

$\mathrm{f_{ren}}$ is defines the renewable fraction (RF), $\mathrm{E_{nonren}}$ denotes the non-renewable electrical production (kWh/year), the energy sold to the grid in kWh/year (included in $\mathrm{E_{served}}$, $\mathrm{H_{nonren}}$ presents the non-renewable thermal production (kWh/year), $\mathrm{E_{served}}$ is the total electrical load served (kWh/year) and $\mathrm{H_{served}}$ is the total thermal load served (kWh/year)

The Unmet Load

The load that the electric system model is unable to meet is defined as unmet load. This happens when the required load exceeds the available electricity. It can be obtained using the following eqn. (5) (Oladigbolu et al. 2023, p. 15).

$$\text{Unmet Load} = \frac{\text{Annual non−served Load}}{\text{Total Annual Load}} \qquad (5)$$

Levelized cost of hydrogen (LCOH)

The levelized cost of hydrogen (LCOH) measures the average cost per unit of hydrogen generation and distribution during the system’s entire life cycle (Rong et al. 2025, p. 839).

3 Research Methods

Various approaches can be followed in performing research. Several criteria influence the choice of research techniques, such as the goal of the study, the nature of the research questions to be addressed, and the resources available (Badhan, 2020, p. 4). A description of the selected research approaches utilized in completing this thesis study is presented in this section. Furthermore, it will also justify the approaches that were not chosen for this study.

3.1 Description of the Research Approach

A research approach, according to Babbie (2004), is a strategy that includes several choices on the sample to be examined, the research approaches, and the goal. Additionally, the most effective study designs include various research methods, leveraging their distinct advantages (Badhan, 2020, p. 4).

Triangulation is the process of integrating at least two different theoretical viewpoints, methodological approaches, sources of data, researchers, or techniques for data analysis (Thurmond, 2001, p. 1). According to Brender (2006), triangulation is a scientific strategy that applies many techniques to measure a comparable trait to compensate for shortcomings in the study methodology. Four categories of triangulation were mentioned by Denzin (1970), which are methodological triangulation, theory triangulation, investigation triangulation, and data triangulation (Noble and Heale, 2019, p. 67). According to Denzin (1978), the data triangulation approach entails utilizing many data sources for a single study. This approach may combine qualitative and quantitative methods to provide a valuable source of data with internal validity checks (Denzin, 1978; Hoque et al., 2018). Cross-validating the data from various sources, employing a particular strategy to obtain information, and utilizing the strengths of all the data types collected can all be beneficial to research (Lukka et al., 1989; cited in Badhan, 2020, p. 4). The data triangulation approach was selected as the research strategy for completing this study. The study will emphasize simulation-based case studies with two different hybrid storage models utilizing HOMER Pro software optimization. The case study involved technical and economic feasibility analysis, as well as the environmental assessment of the multi-energy storage hybrid systems with renewable energy sources, to develop a cost-effective, reliable, and environmentally friendly EV charging solution in the Arctic region. However, the simulation is conducted based on the obtained data from the energy expert and researchers' opinions through a quantitative survey. A brief literature review of the previously done research supports understanding the research topic, technical specifications, and economic properties and finding the study gaps. Additionally, the review provided the cost information for some components assumed in the simulation and the preparation of survey questionnaires.

3.2 Alternative Methods

Meta-analysis is a method for examining study findings as they are generally presented in research papers (Chibba, 2007). A meta-analysis provides an organized summary of findings from studies. It offers a methodical approach to managing data from numerous published studies. A meta-study can be conducted as quantitative or qualitative. A major component of quantitative meta-analysis is defining an effect size statistic, which is an index used to represent study findings. This statistic must be able to represent the quantitative findings of a group of research studies in a standardized manner that allows for meaningful numerical comparison and analysis between the studies. There are distinctions between performing a meta-analysis and a literature review. A literature review as per Chibba (2007) entails examining past studies and hypotheses. A literature review applies to practically all kinds of research that discloses findings, but a meta-analysis is limited to empirical studies using actual data. A meta-study necessitates the development of clear research questions and a particular conceptual framework, both of which contribute to a more thorough synthesis and comprehension of a phenomenon. A literature review entails examining past studies and hypotheses (Chibba, 2007, p. 32). A meta-analysis might be used for this study, but the literature retrieved from the initial search across numerous databases only produced a small number of relevant studies that matched the study topics or conditions, such as the Arctic region. However, a brief literature review was undertaken to have a better grasp of the study fields and technologies and to find sources of information needed to prepare survey questions and comprehend simulation calculations.

An interview could also be used as an alternative to the approach chosen for this study. The interview method uses listening and questioning to generate meanings and information (Lincoln et al., 2005; Badhan, 2020, p. 8). It is regarded as a qualitative research method that facilitates comprehension of the detailed opinions and experiences of individuals or a particular group of participants on a specific strategy, program, or circumstance (Boyce and Neale, 2006). Interviews are a useful way of tracking down specific questionnaire responses to investigate them further (McNamara, 1999). Like the survey, the researcher can interview people in person, over the phone, or online (Badhan, 2020, p. 11).

In this study, an interview was not conducted considering the convenience of the researcher and the participants with respect to time, availability, and location. previously conducted research. However, the data triangulation strategy used to obtain the results in this study involves a quantitative survey and a simulation-based case study.

3.3 Selected Research Strategy

A simulation-based case study with HOMER Pro software is selected as the main methodological approach following a quantitative survey for this research. Through data triangulation involving survey and case study, the results will be evaluated finally. The diagram in Figure 1 illustrates the research strategy followed in this study.

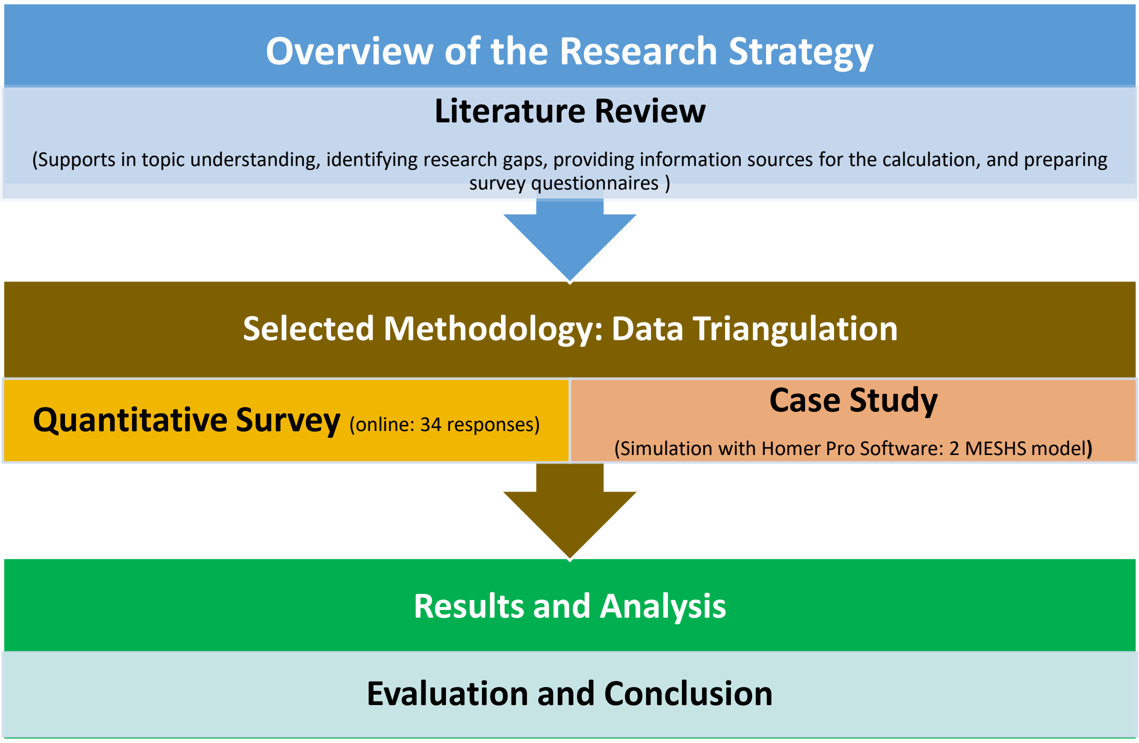


Figure 1. Selected research strategy

3.4 Data Collection and Analysis

- Primary data were obtained through an online survey using Microsoft Forms and a QR code. The review of the previous research helped while preparing the survey questionnaires.
- The renewable energy resources (solar irradiation, wind speed, air temperature) data necessary for the simulation were collected from the NASA POWER databases accessed via HOMER Pro software, ensuring reliable and site-specific inputs for the case study.
- Cost information and technical specifications regarding the components of the multi-energy energy storage system and EV charging infrastructure were also used from the provided data of HOMER Pro software and additionally from the secondary sources, including previous research articles, journal proceedings, book chapters, and thesis papers from various sources like ScienceDirect, Energy Proceedings, IEEE Xplore, ResearchGate, MDPI, the EU Commission, IEA, and some miscellaneous web-sites.

- Data analysis techniques include descriptive statistics with interpretation of survey results, sensitivity analysis, and comparison of the experimental data in the simulation

3.5 Quantitative Research - Survey

Surveys are the simplest and most cost-effective method of gathering data for quantitative research, and they contain important statistics (Visser et al., 2000). Using a survey as a quantitative research approach entails examining the in-depth work done in the field, gathering data globally without physically visiting each responder, and producing accurate results (Visser et al., 2000). According to Badhan (2020, p. 12), survey-based data collection is the most practical way to gather and analyze data. It also offers a numerical representation of the population's attitudes, opinions, and trends by analyzing a sample of the population (Badhan, 2020, p. 9). In order to generalize the findings from a single sample to a larger population, the survey approach, as described by Babbie E. (1990), uses a standard format and questionnaires.

Visser et al. (2000) identified four fundamental survey design types: cross-sectional, repeated cross-sectional, panel, and mixed design surveys (Badhan, 2020, p. 12). Cross-sectional surveys are used to evaluate the relationships between variables and to distinguish between subgroups; repeated cross-sectional surveys are used to evaluate the relationship between the dependent and independent variables over a period of time; panel surveys help predict changes with time and evaluate until previous survey levels remain valid; and mixed design surveys maximize the advantages of other survey methods by utilizing two or more survey techniques (Visser et al., 2000; Badhan, 2020, p. 12). The survey can use either of the two question types outlined by Badhan (2020): closed-ended or open-ended. Participants typically have pre-populated solutions to the closed-ended question. Closed-ended questions can be classified as ranking, drop-down, or multiple-choice. Participants in closed-ended questions select from a list of pre-selected answers rather than being able to respond spontaneously. The purpose of these question patterns is to produce measurable information that is simple to interpret or code. An open-ended question, on the other hand, is designed to elicit a meaningful response and to generate qualitative data by drawing on the subject's background and emotions.

Additionally, compared to closed-ended questions, open-ended questions need to be more objective and less leading (Marx, 2019; Badhan, 2020, p. 12). When answering an open-ended question, all respondent responses must first be grouped for additional analysis. It may be interpreted as negative, positive, or neutral following a thorough investigation. Important terms that the participant used and the examples that were included in the questions should be noted. Additionally, the researcher's own words should be used to interpret the feedback from the participant, intending to improve the research output. Analyzing open-ended questions is found to be more challenging than closed-ended ones (Badhan, 2020, p. 12). For survey results to be meaningful, a better survey analysis process is required. There are several ways to analyze survey data, including manually and with software. Additionally, survey data may be textual or numerical (Marx, 2019; Badhan, 2020, p. 11).

This study investigated stakeholders’ perspectives, including experts and engineers from the energy industry, researchers, policymakers, academics, and local energy enthusiasts, of multi-energy hybrid storage-based EV charging infrastructure in Arctic regions through a quantitative survey. The research student prepared around 35 questionnaires for the survey, comprising 34 quantitative closed-ended questions and one open-ended feedback option. The knowledge gained from previous research in the field and the gaps found throughout the review served as the foundation for the questionnaires' design. The questionnaires include pre-populated answers; however, the researcher employed a mixed strategy by incorporating open-ended feedback (Q 35) to present a novel solution from the participants' perspectives. The design of the questionnaires includes
Closed-ended (34): Likert scales, multiple-choice, and rating and ranking patterns for quantitative analysis.
Open-ended (1): Text-based feedback (qualitative insights)
The thesis supervisor authorized the questions. The research student participated in the energy week event, which was held in Vaasa City Hall, Finland, from March 16 to 19, 2025. The questionnaires were segmented as

- Generic background information about the participants (Q1-Q6)

- Cost factors assessment (Q7-Q13)
- Technical feasibility in arctic conditions (Q14-Q13)
- Environmental impact (Q19-Q27)
- Social/Community-related factors (Q28-Q30)
- Policy Measures (Q31- Q34)

The questionnaires were initially prepared, which included a Microsoft Forms link, and 25 printed copies were physically distributed on the first day of the energy week events. However, the printed survey copies returned with some incomplete answers. Therefore, the questionnaires were updated with a QR scanner code (added in the Appendices) and distributed again to the targeted participants during the entire period of Energy Week. With QR codes, people showed more interest in participating than in the printed paper copies. In the meantime, the contact information was collected from the industry personnel and other energy enthusiast visitors from the event. The targeted stakeholders were grouped as technical experts (engineers), business investors or management personnel, energy researchers and academics, regulatory authorities (policymakers), and local energy students and residents. The survey form link and QR code of the questionnaires were then sent to around 65 people within Finland, Sweden, and Norway via email and LinkedIn. The participation kept anonymously targeting more spontaneous participation. A generic reminder notification was also sent to all the targeted stakeholders by email within 15 days after initial delivery.

A total of 34 responses were collected. However, only 5 responses provided open-ended feedback in Q35. Participants' education levels presented were master’s (22), PhD (4), and bachelor's (8). The background information details for the participants (anonymous) are provided on Table 2 as,

Table 2. Participants' background information

Background Information	No of Participants	Response rate (%)
Engineers (Electrical/Mechanical/Civil/ Environmental/Energy/Industrial/IT)	20	58.8%
Researcher/Academic/Energy Enthusiast	9	26.5%
Business/Management/Industry Personnel	6	17.6%
Policy Maker/Regulatory Authority	2	5.9%
Local Inhabitant and General Student	1	2.9%

From the background data of the 34 respondents illustrated in Table 2, twenty respondents (58.8%), including people with technical backgrounds or engineers, participated in the survey. Additionally, around nine (26.5%) participants had a research background, including academic, doctoral, or post-doctoral researchers in the energy field, and six participants (17.6%) had a background in business or management. Among the total thirty-four participants, two were involved with policy making (5.9%), and only one of the participants presented as a resident or general student (2.9%). Four participants held more than one background; for instance, two participants had both research and engineering backgrounds, one participant presented a background in both research and business or industry, and one participant held an engineering and business background.

Regarding the knowledge level of Arctic weather conditions amongst participants, one (1) held the least knowledge, two of the participants (2) had a moderate level, eight of them had a normal (8) understanding, ten of the participants (10) presented a high level of knowledge, and eleven (11) of the participants held advanced knowledge. So, the participants are mostly presenting an advanced level of knowledge regarding the Arctic weather conditions.

A moderate level of awareness of renewable energy sources is possessed by two (2) participants, a normal understanding by eight (8), a high level of knowledge by thirteen (13), and advanced knowledge by eleven (11). Hence, the majority of the participants demonstrated a high level of knowledge regarding renewable energy sources, such as solar, wind, and so on.

Now, about eleven individuals (32.3%) indicated a high level of understanding, about fourteen of the participants (41.1%) had a medium level of knowledge, three of them (8.8%) had poor knowledge, five of the participants (14.7%) ranked low levels of understanding, and one of them (3.1%) did not rank his level of knowledge on energy systems. Therefore, the highest ranking of participants resulted in a medium knowledge level of the energy storage system.

Finally, while exploring the knowledge level on EV charging infrastructure amongst participants, one (1) held the least knowledge, two of the participants (2) had a moderate level, thirteen of them had a normal (13) understanding, ten of the participants (10) presented a high level of knowledge, and seven (7) held advanced knowledge. So, the participants are mostly presenting a normal level of knowledge regarding the EV charging infrastructure.

In sum, most of the participants hold technical and research backgrounds, and the majority have a master's level of education. Some even have diverse backgrounds. Assessing the knowledge level of the key aspects of this study, the participants demonstrated an advanced level of knowledge regarding the Arctic weather conditions and a high level of knowledge regarding renewable energy sources. However, a medium knowledge level on the energy storage system and a normal level of knowledge regarding the EV charging infrastructure.

3.6 Case Study - Simulation

A case study is conducted with two different storage hybrid models in this section, which follows a simulation of an off-grid multi-energy storage hybrid system (MESHS) to determine the most cost-effective, economically feasible, and eco-friendly EV charging system solution for the Arctic region with renewable energy sources.

Tools for energy simulation.

HOMER is a popular software used for microgrid design, simulation, and sensitivity analysis. It is the best software used for simulating hybrid energy designs. The software was developed by the National Renewable Energy Laboratory (NREL) in the U.S. in 1993 (Rong et al. 2025). It is used to analyze both grid-independent and grid-connected forms in a simplified manner for various applications. This software accomplishes three major tasks: simulation, optimization, and sensitivity evaluation. For the simulation, HOMER models hourly the performance of each of the system subunits to ensure the optimal possible matching between the energy demand and supply. Various system designs are modeled in the optimization section to determine those systems that satisfy the technical constraints and fulfill the charge demand at a lower life-cycle cost. Finally, HOMER performs numerous optimization operations with various ranges of input variables to determine the effects of changes in input parameters on the selected system in the sensitivity analysis section (Oladigbolu et al., 2023, p. 5). HOMER Pro x64 version 3.18.4 (Pro edition) was employed for this study.

Evaluation Criteria

Cost Evaluation: The cost criteria for the evaluation include the life cycle cost (LCC), or the total net present cost (NPC), levelized cost of energy (LCOE), levelized cost of storage (LCOS) or levelized cost of hydrogen (LCOH), initial capital expenses (CAPEX), and operational expenses (OPEX) (Rong et al. 2025, p. 839).

Economic Evaluation: The economic parameters included the internal rate of return (IRR), return on investment (ROI), and simple payback period.

Technical Viability: In addition, finding the most viable system of the hybrid systems, the study considers the renewable fractions (RF), unmet load, and the amount of excess electricity (Rong et al. 2025, p. 844).

Environmental Emission Measurement

Carbon dioxide emissions, particularly from diesel and other fossil fuel-powered generators, account for most of the greenhouse gas (GHG) emissions by the hybrid-energy systems (Rong et al. 2025, p. 839). In this study, HOMER measures the amount of greenhouse gas emissions, including carbon emissions, in kilograms per year (kg/year).

Sensitivity Analysis

The sensitivity analysis examines various diesel prices (€) to assess how they affect other cost and performance parameters, the consumption of fossil fuel (diesel) by the generator, and the costs and emissions associated with multi-energy storage systems that support off-grid electric vehicle (EV) charging stations.

3.6.1 Simulation Process of the multi-energy hybrid storage system (MESHS)

In this section, the proposed multi-energy hybrid storage system (MESHS) and simulation are conducted with HOMER Pro software to experiment with technical viability, economic effectiveness, and emission measurement for the off-grid EV charging station.

For a remote off-grid community's electricity demand according to Majdi et al. (2021), several steps need to be followed, including choosing a good location for the case study; defining the electricity demand load data, setting all the components of the microgrid design, energy resources (generators and turbines), storage devices (batteries), rectifiers of AC to DC (converters), and predeterminers of the electrical system (controllers), acquiring environmental data associated with the energy resources, such as wind, water, and fuel types, optimizing the design by determining the location, size, and number of devices needed to harness energy resources; and testing the feasibility and financial viability of the optimized microgrid design.

The steps outlined in Figure 2 were followed for the MESHS optimization and assessment as follows:

- Selecting a suitable location for the case study.
- Adding renewable resources (solar irradiation/air temperature/wind speed)
- Fixing primary load profile (EVCS AC load: 600 kWh/day)
- Optimizing and simulating MESHS Model 1 with H_2 storage (PV/WT/Generator (D)/Converter (AC-DC)/Electrolyzer/HTank/Fuel Cell (H_2)/Controller (LF) and external H_2 Load and MESHS Model 2 with battery storage (PV/WT/Generator (D)/Converter/Lithium-ion Battery/Controller for the proposed EV charging infrastructure.

- Assessing the best multi-energy storage hybrid system (MESHS) model with H_2 storage and lithium-ion battery storage
- The key criteria for evaluating the simulated outcomes included the lowest total NPC, CAPEX, OPEX, LCOE, LCOH/LCOS, and emission measurement from HOMER Pro.
- Additionally, the financial criteria for return on investment (ROI), internal rate of return (IRR), and payback period (simple) were also observed.
- The study analyzed the reliability criteria, including renewable fractions (RF), excess electricity, unmet load, and capacity shortages.
- The optimization results were compared.
- Sensitivity analysis was conducted for MESH Model 1 and Model 2 using various diesel prices (€1.70, €1.80, and €2.00), and performance changes were observed, and sensitive cases were considered.

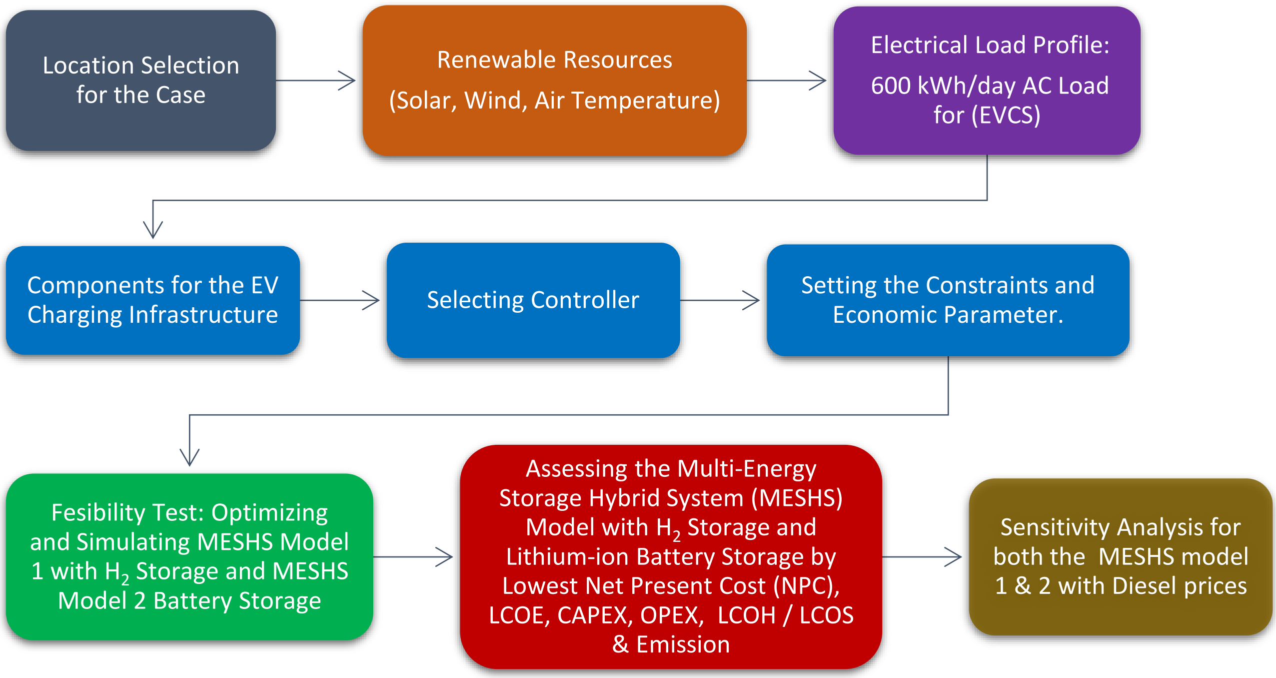


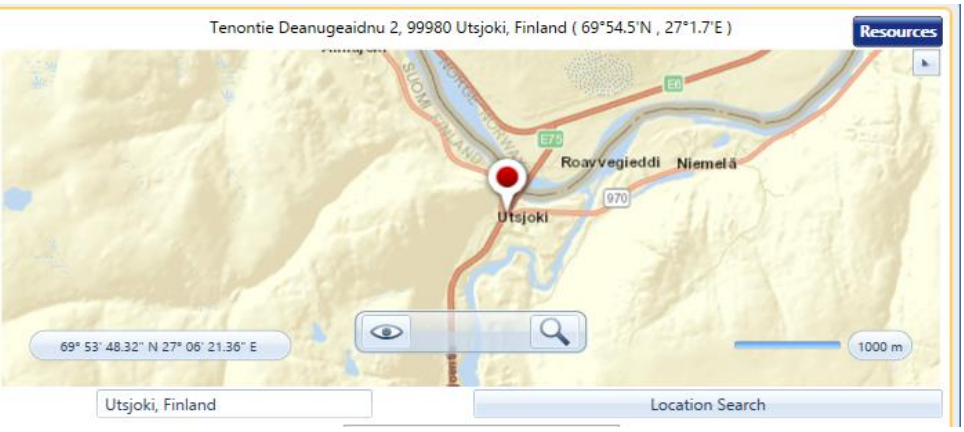
Figure 2. Steps of the simulation and feasibility assessment of the MESHS model with HOMER

3.6.2 Location Selection for the Case Study

According to Sayed et al. (2024), the technical feasibility of hybrid energy systems depends on the conditions of geographic location and climate. The selected test site for the

EV charging station is Utsjoki, Finland. It is in upper Lapland and close to the borders of Norway. Latitude (N) 69°54.5' and Longitude (E) 27°1.7'. The region is chosen for its abundance of renewable energy sources. For example, this area has clean air, which provides ample wind resources. Additionally, the longest duration of midnight sun during the summer enables solar power to be generated during extended daylight. Furthermore, the river valley provides hydropower potential. The population of this area is around 1200. Furthermore, it is an important northern location in Finland to enjoy traditional livelihoods, northern lights, spring snowdrifts, and the Arctic Ocean, which present opportunities for border trade, sustainable tourism, and experiencing the culture of the close-knit Arctic community (Utsjoki, 2025).

To ensure a reliable power supply for promoting sustainable mobility while reducing the power load to the grid and limiting the dependence on fossil fuels, like diesel, the proposed EV charging infrastructure integrating a multi-energy storage system with the locally available renewable sources is considered as a potential solution to environmental emission reduction. HOMER Pro software is used to determine the case location to optimize the hybrid energy systems for the EV charging infrastructure (Sayed et al., 2025). The geographic coordinates and map of the chosen place are depicted in Figure 3 using HOMER Pro software.


Tenontie Deanugeaidnu 2, 99980 Utsjoki, Finland (69°54.5'N , 27°1.7'E)

69° 53' 48.32" N 27° 06' 21.36" E

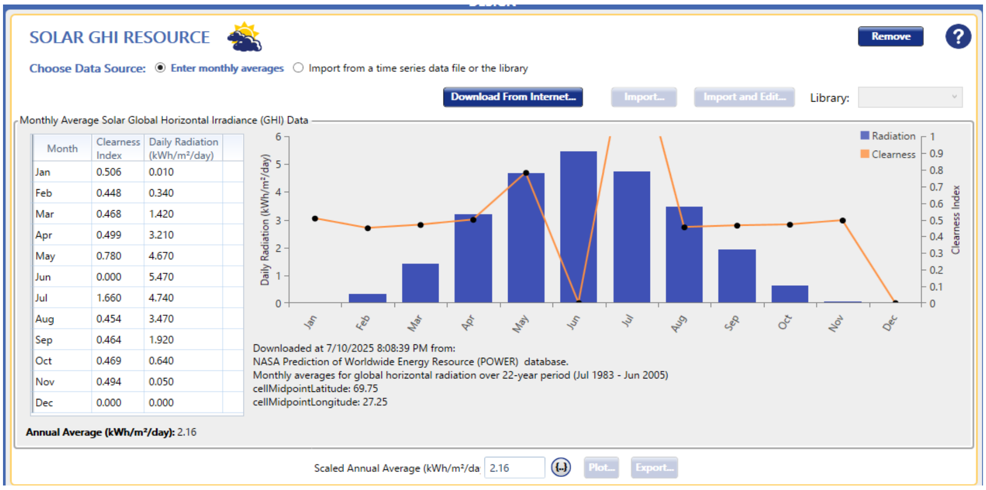
Utsjoki, Finland

Figure 3. Geographic location of the EV charging station at Utsjoki, Finland

3.6.3 Renewable Resources Data

When using HOMER Pro for energy modeling, wind speed, air temperature, and solar radiation are crucial inputs (HOMER Energy, n.d.-e). This information can be obtained from user libraries, time series data files, or the internet. By recording comprehensive data about intermittent renewable sources at hourly intervals, HOMER Pro improves modeling accuracy and makes accurate forecasts and simulations possible (Lambert, 2006; cited in Kalliovalkama, 2024, p. 36). This section presents information about the RE resources used for the simulation of the Multi-Energy Storage Hybrid System (MESHS) for the EV charging station.

The annual average solar global horizontal irradiance (GHI) data for Utsjoki over 22 years (Jul 1983 – Jun 2005) is 2.16 kWh/m²/day, obtained from the NASA (POWER) database, which is depicted in Figure 4. The minimum average GHI value of Utsjoki is observed as 0.00 kWh/m²/day in December, and the clearance index is 0.00. The highest global horizontal irradiance (GHI) value noticed in June is 5.47 kWh/m²/day, and the clearance index is 0.00.



Choose Data Source: ● Enter monthly averages ○ Import from a time series data file or the library

Library:

Monthly Average Solar Global Horizontal Irradiance (GHI) Data

Month	Clearness Index	Daily Radiation (kWh/m²/day)
Jan	0.506	0.010
Feb	0.448	0.340
Mar	0.468	1.420
Apr	0.499	3.210
May	0.780	4.670
Jun	0.000	5.470
Jul	1.660	4.740
Aug	0.454	3.470
Sep	0.464	1.920
Oct	0.469	0.640
Nov	0.494	0.050
Dec	0.000	0.000

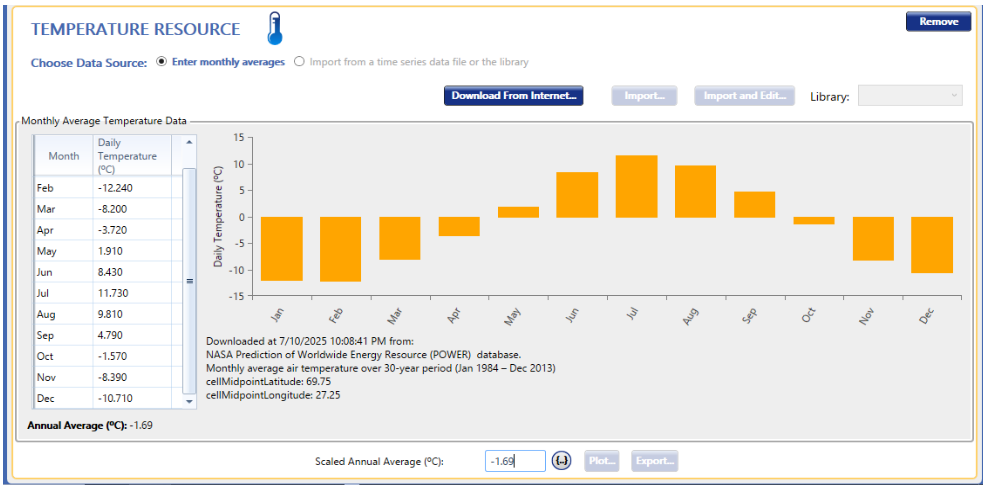
Downloaded at 7/10/2025 8:08:39 PM from:
NASA Prediction of Worldwide Energy Resource (POWER) database.
Monthly averages for global horizontal radiation over 22-year period (Jul 1983 - Jun 2005)
cellMidpointLatitude: 69.75
cellMidpointLongitude: 27.25

Annual Average (kWh/m²/day): 2.16

Scaled Annual Average (kWh/m²/da 2.16

Figure 4. Monthly average solar GHI data of Utsjoki, Finland

The annual average air temperature over 30 years (January 1984 to December 2013) of Utsjoki is -1.69°C, presented in Figure 5. The lowest temperature recorded in February in this selected location is -12.24°C, whereas the highest recorded average temperature is 11.73°C, observed in July.



Choose Data Source: ● Enter monthly averages ○ Import from a time series data file or the library

Monthly Average Temperature Data

Month	Daily Temperature (ºC)
Feb	-12.240
Mar	-8.200
Apr	-3.720
May	1.910
Jun	8.430
Jul	11.730
Aug	9.810
Sep	4.790
Oct	-1.570
Nov	-8.390
Dec	-10.710

Downloaded at 7/10/2025 10:08:41 PM from:
NASA Prediction of Worldwide Energy Resource (POWER) database.
Monthly average air temperature over 30-year period (Jan 1984 – Dec 2013)
cellMidpointLatitude: 69.75
cellMidpointLongitude: 27.25

Annual Average (ºC): -1.69

Scaled Annual Average (ºC): -1.69

Figure 5. Monthly average temperature data of Utsjoki, Finland

The monthly mean velocity of the wind data at 50 m above the earth's surface, gathered at the case location Utsjoki, Finland, for 30 years (January 1984 to December 2013), is displayed in Figure 6. This region records the highest average wind speed of 7.36 m/s in February. The annual average velocity of the wind is 5.93 m/s.

Choose Data Source: ● Enter monthly averages ○ Import from a time series data file or the library

Monthly Average Wind Speed Data

Month	Average (m/s)
Jan	7.340
Feb	7.360
Mar	7.120
Apr	6.210
May	5.560
Jun	4.910
Jul	4.600
Aug	4.350
Sep	4.880
Oct	5.680
Nov	6.160
Dec	6.980

Annual Average (m/s): 5.93

Downloaded at 7/10/2025 8:03:27 PM from:
NASA Prediction of Worldwide Energy Resource (POWER) database.
Monthly average wind speed at 50m above the surface of earth over a 30-year period (Jan 1984 – Dec 2013)
cellMidpointLatitude: 69.75
cellMidpointLongitude: 27.25

Wind speed profile:
● Logarithmic
○ Power Law

Surface roughness length (m): 0.01

Scaled Annual Average (m/s): 5.93

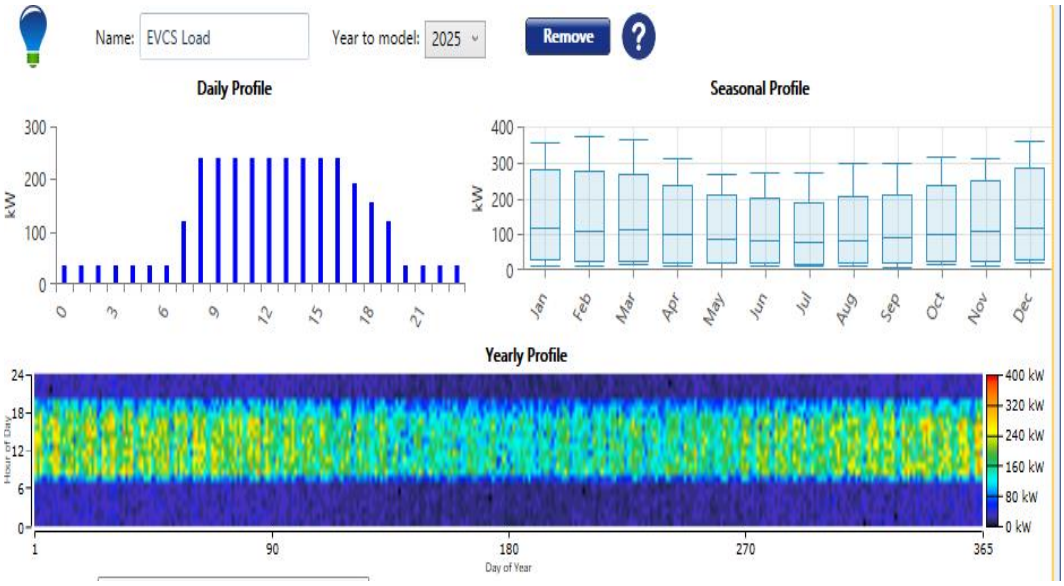
Figure 6. Monthly average data of wind data at Utsjoki, Finland

3.6.4 Electrical Load Profile for the EV Charging System

The load is a part of the system that consumes energy, excluding any potential system losses (HOMER Energy, n.d.-f). The importance of electrical load characteristics in influencing the model's design, component sizes, cost-effectiveness, and overall performance was highlighted by Kalliovalkama (2024). In HOMER Pro, creating the electrical demand necessitates setting up parameters that are necessary for modelling the microgrid. While certain load parameters are set up after the model is added, others are specified in HOMER Pro beforehand. These electrical load parameters, according to HOMER Energy (n.d.-f), include the simulation year, advanced efficiency settings, AC or DC load type, the scaled annual average kilowatts per day, and variation in day-to-day and timestep percentages (cited in Kalliovalkama, 2024, p. 33). Rong et al. (2025) estimated an annual average load for a small-scale EV station in Makkah, Saudi Arabia, was 1081 kWh per day with a peak energy demand of 229.61 kW, which involved around 60 electric vehicles (EVs). The EVs were expected to have a maximum daily electrical load of 600 kWh, and additionally, the battery energy demand was 30 kWh (Rong et al., 2025, p. 840). According to the report of the Global EV Outlook (IEA, 2025), more public charging stations should be installed in EU nations in accordance with the Alternative Fuels Infrastructure Regulation (AFIR). This (AFIR) regulation mandates the installation of fast-charging stations for vehicles of at least 150 kW, like cars and vans, every 60 km along the Trans-European Transport Network (TEN-T) road by 2025. Every station should have the minimum daily total power capacity of 400 kW, increasing to 600 kW by the end of 2027 (IEA, 2025, p.101). The selected location for the study is not directly linked to the TENT-T core and comprehensive network road. However, the test EV charging location is connected to route E 75, which is a part of the international E-road network and links Norway, Finland, the Czech Republic, Poland, Hungary, Serbia, Slovakia, North Macedonia, and Greece (Wikipedia, 2025). This road has many possibilities for trade, tourism, and importance due to its close border connection (Utsjoki, 2025); however, there are only limited charging facilities. In addition, to enhance EV adoption by reducing the dependence on fossil fuel as well as reducing carbon emission, developing charging facilities using sustainable resources is crucial (Alanazi, 2023). Additionally, ultra-fast charging demand has doubled in Europe since 2022, demonstrating the continued growth of fast charging. In the European Union, about 20% of ultra-fast chargers—including those in Finland, Denmark, Germany, and France—deliver 350 kW or more of electricity power. Only a limited number of expensive electric vehicles can now be charged at this rate. The charging station operators, like BP Pulse, FastNed, and Iberdrola, are expanding their stations in preparation for future demand (IEA, 2025, p. 103).

The electrical load is assumed for the proposed MESHS integrated EV charging station based on the growing demand for fast charging in EU countries as per the IEA Global Outlook report (2025), as well as considering the Arctic weather conditions, local communities' or remote locations' charging needs, supporting the expansion of tourism in the Arctic region, and reducing the grid load. HOMER shows that, when the peak month of January is considered, the highest average electrical load for the commercial EV charging station in Utsjoki is 2479.4 kWh/day.

With an average load of 80 kW to 100 kW, it is estimated that 20 to 30 EVs can be charged (80%) every day in the optimized MESHS of the EV station. The peak charging demand exists between 7:00 and 19:00. About 20 EVs can be charged in this time, while the test charging station can power an additional 10 to 15 EVs on average at 40 kW during the remaining hours of the day. Each EV was estimated to have a daily battery energy capacity of 30 kWh - 35 kWh (Rong et al., 2025, p. 840; Oladigbolu et al., 2023, p. 15). Hence, the total annual average electrical load for the optimized Electric Vehicle Charging Station (EVCS) is hypothetically scaled as 600 kWh per day AC load in HOMER Pro software with the peak load of 99.44 kW and a load factor of 0.27 (Figure 7). For the data analysis of the EVCS load, we considered a time-step of 20% and day-to-day random variability of 10% (Oladigbolu et al., 2023, p. 15).



Name: EVCS Load

Year to model: 2025

Figure 7. EVCS Load profile of 24-hour period at Utsjoki, Finland

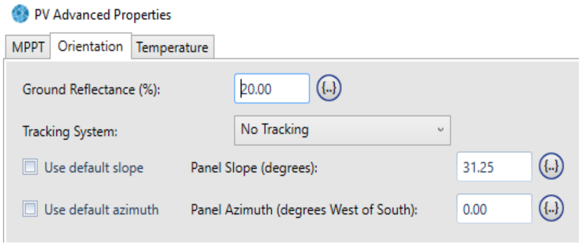
3.6.5 System Description

One of the crucial phases, according to Rao et al. (2024, p. 3), is creating the infrastructure for electric vehicle charging. It can be constructed in a variety of ways depending on the user's needs. For the EV charging system at the chosen location in Utsjoki, Finland, renewable energy sources, components, and storage systems were selected based on a review of prior research and survey outcomes. Wind and solar PV are considered the main renewable sources, and the diesel generator is considered a backup. Due to the limitations of the HOMER Pro program, which only permits four optimization variables, the optimization is carried out using the two energy storage systems and compares emissions and cost. One optimum model (model 1) incorporates solar photovoltaics, wind, a diesel generator, a fuel cell, an electrolyzer, a hydrogen tank, a hydrogen load with the charging system, and a system converter (bidirectional AC-DC). Another model (model 2) comprises lithium-ion battery storage, PV, wind, a diesel generator, and a bi-directional AC-DC system converter. To facilitate the charging of various EVs, the charging stations themselves had modules with connectors. For longer routes and high-demand scenarios, fast charging is taken into consideration. However, slow charging uses less energy and can be utilized overnight (Rao et al., 2024, p. 3). For the optimized charging stations, both fast and slow charging choices are considered due to growing demand and local conditions.

3.6.6 Components

PV Systems

Photovoltaic systems convert sunlight directly into electrical power by using semiconductor materials and the photovoltaic effect. PV systems are currently an essential component of renewable energy due to their affordability and efficiency (Xin et al., 2024, p. 3). While wind turbines are considered the best renewable resource to power the long winter nights in the Arctic, solar PV also offers ample electricity during the long summer days. For the MESHS model of the EV charging station, the SunPower E20-327 flat plate photovoltaic panel was taken into consideration. The panel is made of monocrystalline silicon and consists of 96 cells on a flat plate. The rated capacity of the panel was 0.327 kW. The operating temperature was 45°C, and the temperature coefficient was -0.380/°C. The efficiency of this specific PV panel type (20.4%) in a standard situation is the primary reason it was selected for the experiment. Without a tracking system, the solar power arrays are oriented (Figure 8) with a 31.25% slope and a 0% azimuth (Rong et al. 2025, p. 840; Das et al. 2020, p. 2).



Ground Reflectance (%): 20.00

Tracking System: No Tracking

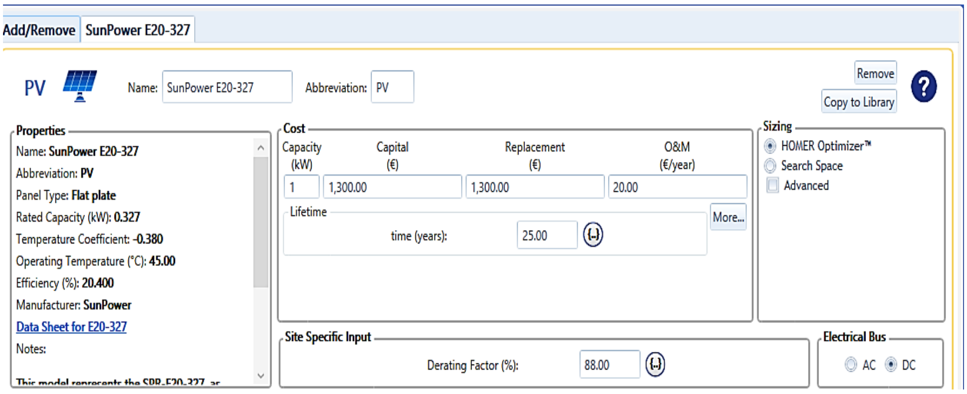
☐ Use default slope Panel Slope (degrees): 31.25

☐ Use default azimuth Panel Azimuth (degrees West of South): 0.00

Figure 8. PV panel (SunPower E20-327) orientation

The PV's capacity is optimized using the HOMER optimizer. The panel's derating factor is 88%, and no tracking technique was chosen for optimization. The PV module has a 25-year lifespan and was connected to the DC electrical bus. The estimated annual O&M expenses were 20€ per kW, while the capital and replacement costs were 1300€ per kW

(Das et al. 2020, p. 2). The Sun-Power E20-327 PV panel's technical specifications and pricing are presented in Figure 9. & Table 3.



Name: SunPower E20-327
Abbreviation: PV

Properties
Name: **SunPower E20-327**
Abbreviation: **PV**
Panel Type: **Flat plate**
Rated Capacity (kW): **0.327**
Temperature Coefficient: **-0.380**
Operating Temperature (°C): **45.00**
Efficiency (%): **20.400**
Manufacturer: **SunPower**
Data Sheet for E20-327
Notes:

Cost

Capacity (kW)	Capital (€)	Replacement (€)	O&M (€/year)
1	1,300.00	1,300.00	20.00

Lifetime
time (years): 25.00

Sizing
● HOMER Optimizer™
○ Search Space
☐ Advanced

Site Specific Input
Derating Factor (%): 88.00

Electrical Bus
○ AC ● DC

Figure 9. PV panel (SunPower E20-327) properties.

Table 3. Costs of the PV panel (Rong et al. 2025, p. 842)

Properties	Value
Capital Cost (CAPEX)	1300 €/kW
Replacement Cost	1300 €/kW
Operation and Maintenance (O&M) Cost	20€/kW per year
Life span	25 (years)

According to Rong et al. (2025), the PV array's power (P_{pv}) is impacted by temperature. The following formula can be used to determine the solar cell's power output:

$$P_{PV}=P_r.\ f_{PV}\ R_T\,[1+\alpha_P\,(T_C-25)] \tag{6}$$

Here, P_r is the nominal capacity of solar panel arrays at STC (kW), T_c is the photovoltaic cell temperature (◦C), f_{pv} is the PV derating factor (%), α_p is the temperature coefficient of power (%/C), and P_{pv} is the power output of the PV arrays (Mandal et al., 2018; cited in Rong et al., 2025). To determine the solar cell's temperature, the formula below can be used.

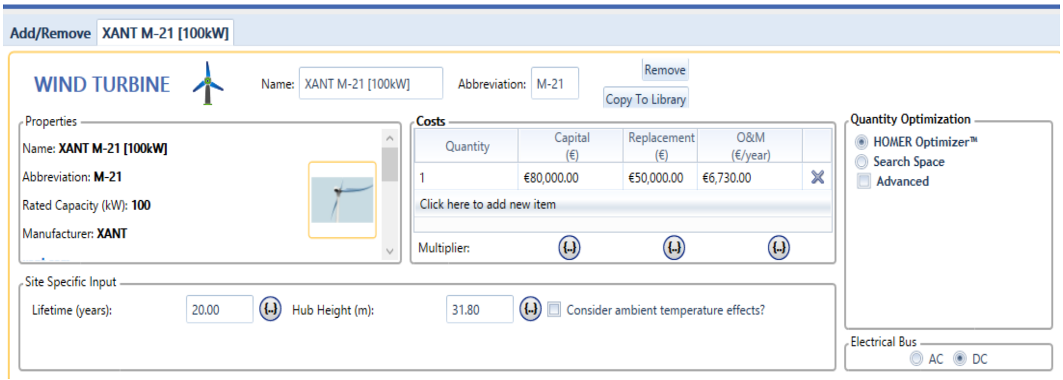
$$T_c = T_a + R_T\left(\frac{T_{c,n}-20}{0{\cdot}8}\right)\left(1-\frac{\eta_c}{0.9}\right) \tag{7}$$

Here, T_a is the ambient temperature (◦C), $T_{c,n}$ is the normal operating cell temperature (NOCT) in degree celsius (◦C), and η_c is the PV arrays' electrical conversion efficiency (%) (Rong et al., 2025, p. 840).

Wind Turbines

Wind turbines use generators, gearboxes, and rotor blades to transform the kinetic energy of the wind into electrical energy. They contribute significantly to the production of renewable energy worldwide and have a variety of designs to suit various environments (Xin et al., 2024, p. 3). Using the resource database (NASA POWER, n.d), load demand inputs, and the catalogue file for the chosen component, most of the wind turbine attributes and characteristics are automatically incorporated into the simulation (HOMER Energy, n.d. -g). Some characteristics can be manually set up, including site-specific inputs and automated or manual sizing. Depending on how the system is designed, the wind turbine can be connected to the microgrid's AC or DC bus. As per HOMER Pro's component catalogue, the lifetime parameter establishes the anticipated length of time the turbine will operate before needing to be replaced. HOMER can adjust ambient temperature, which impacts air density, and the Hub Height (the distance in meters from the ground to the turbine's hub) (HOMER Energy, n.d.-g; cited in Kalliovalkama, 2024, p. 41).

The XANT M 21 wind turbine was chosen for this research because of its high efficiency and some of its economic benefits (Ribbing and Xydis, 2021). The capacity of the WT is optimized using the HOMER optimizer (Zhang et al., 2023; cited in Rong et al., 2025, p. 842). The hub height is 31.80 meters, as illustrated in Figure 10, and the rated electrical power capacity is 100 kW. For this study, the capital cost per XANT M-21 WT is approximately €80,000.00, and the yearly operation and maintenance (O&M) cost is estimated as €6,730 (Youssef et al., 2023, p. 9). After 20 years of lifetime, the replacement cost is considered €50,000 (Table 4) (Rong et al. 2025, p. 842; Oladigbolu et al., 2023, p. 12).



Name: XANT M-21 [100kW]
Abbreviation: M-21

Name: **XANT M-21 [100kW]**
Abbreviation: **M-21**
Rated Capacity (kW): **100**
Manufacturer: **XANT**

Quantity	Capital (€)	Replacement (€)	O&M (€/year)
1	€80,000.00	€50,000.00	€6,730.00

Multiplier:

Lifetime (years): 20.00
Hub Height (m): 31.80
☐ Consider ambient temperature effects?

● HOMER Optimizer™
○ Search Space
☐ Advanced

○ AC ● DC

Figure. 10 Wind Turbine (XANT M-21) specification

Table 4. Costs of the Wind Turbine (Rong et al. 2025, p. 842; Oladigbolu et al., 2023, p. 12).

Properties	Value
Capital Cost	80,000 € / Qty.
Replacement Cost	50,000 € /Qty.
Operation and Maintenance (O&M) Cost	6730 € /year
Life span	20 (years)

The exponential law model is frequently used to practically calculate wind speed variations based on terrain and height, such as 50 m, anemometers, and wind turbine hub heights (Ohunakin et al., 2011). The turbine's output at standard temperature and pressure (STP) condition is depicted in a power curve, which is a frequently used tool for evaluating WT performance (Figure 11). The formula mentioned by Dhundhara et al. (2018) is used to determine the WT's output power under actual operating conditions.

$$P_w(V) = \left(\frac{\rho}{\rho_{\mathrm{stp}}}\right) \cdot P_{ws}(V) \tag{8}$$

In the above equation (8) ρ_{stp} is 1.225 kg/m³ which indicates the air density at standard temperature and pressure (STP). The actual air density is ρ (kg/m³).

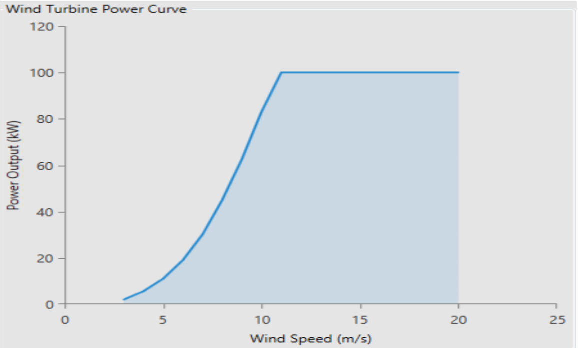


Figure 11. Power Curve of XANT M 21 (100 kW) Wind Turbine

Hydrogen Storage Components

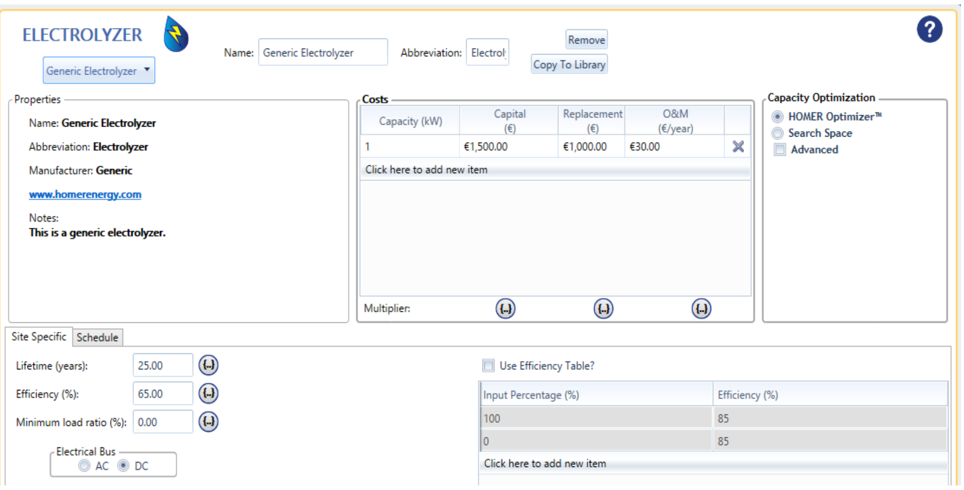
This research focuses on short- and long-term storage options that are compatible with RESs and suitable for microgrids. Rao et al. (2024) claim that hydrogen storage can help with decarbonization by addressing the intermittent nature of renewable energy sources. To minimize energy losses and guarantee that the energy produced is saved for future use, energy storage systems are designed (Rao et al. 2024, p. 3). Götz (2016) asserts that power-to-hydrogen, or power-to-gas, is a useful strategy for balancing RESs by transforming surplus electrical power into hydrogen for storage and future usage (as cited in Kalliovalkama, 2024, p.23). Hunter et al. (2021) mentioned that hydrogen is also being explored as a potential electrical energy storage material. Conceptual hydrogen storage systems driven by renewable energy sources generally include an electrolyzer and storage in tanks, pipes, or underground caverns and can be utilized for re-electrification using economically feasible fuel cells or combustion turbines (Hunter et al., 2021, p. 2079).

Cost, site-specific performance, and other input factors are included in Kalliovalkama's (2024) list of chosen hydrogen components. The assumptions for hydrogen modeling include fixed capacity parameters for both components, a minimum load level, and constant efficiency (HOMER Energy, n.d.-h). Furthermore, it is assumed that electrolyzers consume unused electricity while producing hydrogen power.

The hydrogen module in the HOMER Pro software is also ideal for users who model fuel cells, remote off-grid operations, large industrial processes, or any system with hydrogen production, storage, or consumption. This module adds a reformer, electrolyzer, and hydrogen tank components. It also adds a hydrogen load and stores a hydrogen-fueled generator (HOMER Energy, n.d.-h; Kalliovalkama, 2024, p. 25). One generic hydrogen tank and one generic electrolyzer are included in HOMER Pro. PEM (Proton Exchange Membrane) or AWE (Alkaline Water Electrolysis) electrolyzers are not considered in the simulation models, since it was hard to get compatible input data (Kalliovalkama, 2024, p. 43). The MESHS model 1 in this study includes a hydrogen tank to store the hydrogen produced by the generic electrolyzer and a 100-kW generator as a fuel cell for re-electrification while storing the liquid H_2 produced from the excess electricity for the EV charging infrastructure.

Electrolyzer

Water electrolysis is the most practical method for producing hydrogen from renewable resources. (Rong et al., 2025, p. 843). According to Mazloomi and Sulaiman (2012), the most effective configuration combines a photovoltaic array with a hybrid water electrolysis system with an electrolyzer. The properties of the electrolyzer include several site-specific parameters, such as lifetime, efficiency, minimum load ratio, and electrical bus. The lifetime parameter refers to the number of years the electrolyzer is expected to operate before needing replacement, like the lifetime of wind turbines. (HOMER Energy, n.d.-i; Kalliovalkama, 2024, p. 43). The efficiency parameter (%) represents how efficiently the electrolyzer converts electrical energy into hydrogen molecules. The minimum load ratio indicates the minimum power level at which the electrolyzer can operate at its rated capacity (HOMER Energy, n.d. -i). Operating the electrolyzer below this minimum load ratio can lead to reduced performance, inefficiencies, and potential damage. The choice of AC or DC electrical system affects the electrolyser's efficiency, costs, and overall system reliability (Kalliovalkama, 2024, p. 44).



Name: Generic Electrolyzer
Abbreviation: Electrol

Name: **Generic Electrolyzer**
Abbreviation: **Electrolyzer**
Manufacturer: **Generic**
www.homerenergy.com
Notes:
This is a generic electrolyzer.

Capacity (kW)	Capital (€)	Replacement (€)	O&M (€/year)
1	€1,500.00	€1,000.00	€30.00
Click here to add new item			

● HOMER Optimizer™
○ Search Space
☐ Advanced

Lifetime (years): 25.00
Efficiency (%): 65.00
Minimum load ratio (%): 0.00
Electrical Bus: ○ AC ● DC

☐ Use Efficiency Table?

Input Percentage (%)	Efficiency (%)
100	85
0	85
Click here to add new item	

Figure 12. Electrolyzer’s specification

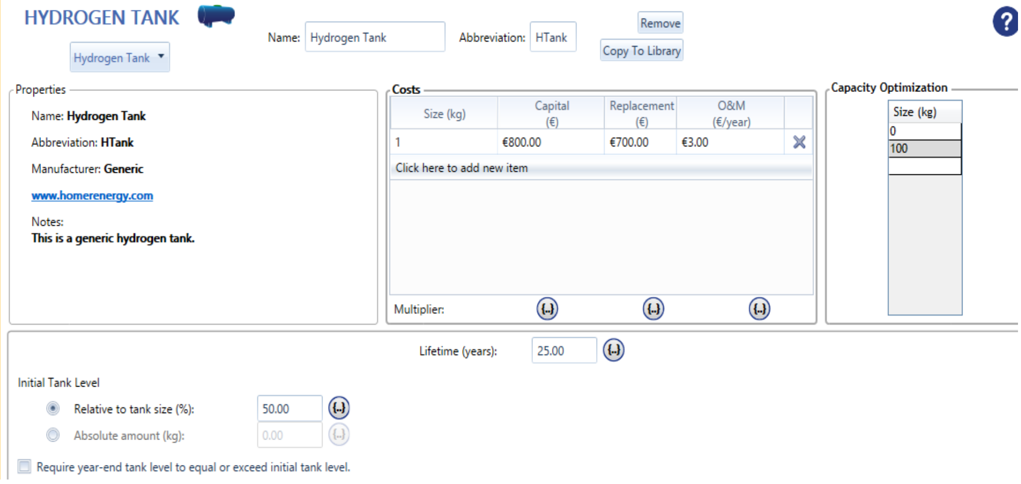
The generic electrolyzer selected for this study has a lifetime of 25 years, efficiency at 65.00 % and a minimum load ratio of 0.00 % while it is connected to the DC electric bus (Figure 12.). The Capital cost for the electrolyzer is considered 1,500 € / kW, the replacement cost 1,000 € / kW, and its O&M costs are 30 € / year as illustrated in Figure 12. and Table. 5 (Al-Badi et al, 2022, p. 6).

Table 5. Cost of the Electrolyzer (Al-Badi et al, 2022, p. 6)

Properties	Value
Capital Cost (CAPEX)	1,500 € / kW
Replacement Cost	1, 000 € / kW
Operation and Maintenance Cost (O&M)	30 € / year
Life span	25 (years)

Hydrogen Tank (HTank)

A hydrogen tank is the component used to store excess hydrogen produced by an electrolyzer, according to the HOMER Pro software description. This stored hydrogen can serve as a source of hydrogen. The tank's initial level indicates the proportion of the tank's size before the simulation begins. The last hydrogen tank parameter specifies whether the year-end tank level needs to be the same as or higher than the starting tank level. When this option is selected, HOMER Pro views the system as unfeasible since the tank level at year-end is less than the starting level (HOMER Energy, n.d.-j; Kalliovalkama, 2024, pp. 44-45).



Name: Hydrogen Tank
Abbreviation: HTank

Name: Hydrogen Tank
Abbreviation: HTank
Manufacturer: Generic
www.homerenergy.com
Notes:
This is a generic hydrogen tank.

Size (kg)	Capital (€)	Replacement (€)	O&M (€/year)
1	€800.00	€700.00	€3.00

Size (kg)
0
100

Lifetime (years): 25.00

Initial Tank Level
● Relative to tank size (%): 50.00
○ Absolute amount (kg): 0.00
☐ Require year-end tank level to equal or exceed initial tank level.

Figure 13. Hydrogen Tank (HTank) Configuration

For this study, the generic hydrogen tank was added to the MESHS model 1. The initial level of the tank was set to 50% relative to its size, as illustrated in Fig. 11. The capital cost for the hydrogen storage tank (HTank) was assumed to be 8.00 € / kW, the replacement cost 7.00 € / kW, and its O&M costs are 3 € / year (Al-Badi et al., 2022, p. 6), as depicted in Table 6.

Table 6. Cost of the Hydrogen Tank (HTank) (Al-Badi et al, 2022, p. 6)

Properties	Value
Capital Cost (CAPEX)	8, 00 € / kW
Replacement Cost	7, 00 € / kW
Operation and Maintenance (O&M) Cost	3 € / year
Life span	(years)

Hydrogen Load

A hydrogen load supplies an extra hydrogen requirement. Configuring the hydrogen load entails Figure 14, exactly as the electrical load. The unmet hydrogen load penalty (€/kg), the maximum unmet hydrogen load percentage, and the electricity value (€/kWh) can all be manually input or imported from a file. The hydrogen load and its larger system depend on defining the demand, amount, time, and limits, even though many of the characteristics are the same as those for the electrical load (HOMER Energy, n.d. -p; Kalliovalkama, 2024, pp. 34-35). For this study location, Utsjoki, an additional community-based load of hydrogen was considered externally at HOMER Pro. The purpose of adding hydrogen load is to produce hydrogen and better utilize the generated excess electricity from the hybrid model. A scaled annual average load of 5.00 kg/day of hydrogen was added to the proposed MESH model (1). With a load factor of 0.2, the scaled average hourly value of hydrogen load is 0.21 kg, with a peak amount of 1.03 kg/hour.

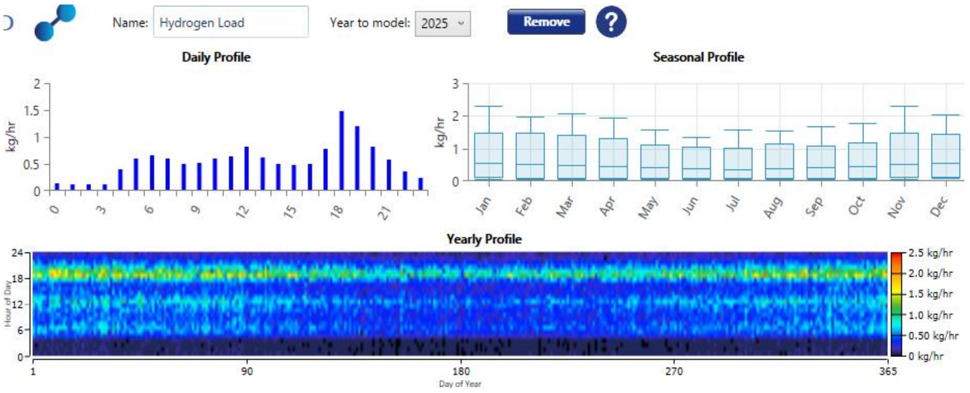

Name: Hydrogen Load
Year to model: 2025

Figure 14. Hydrogen Load Profile of 24-hour period in January at Utsjoki, Finland

Battery Storage

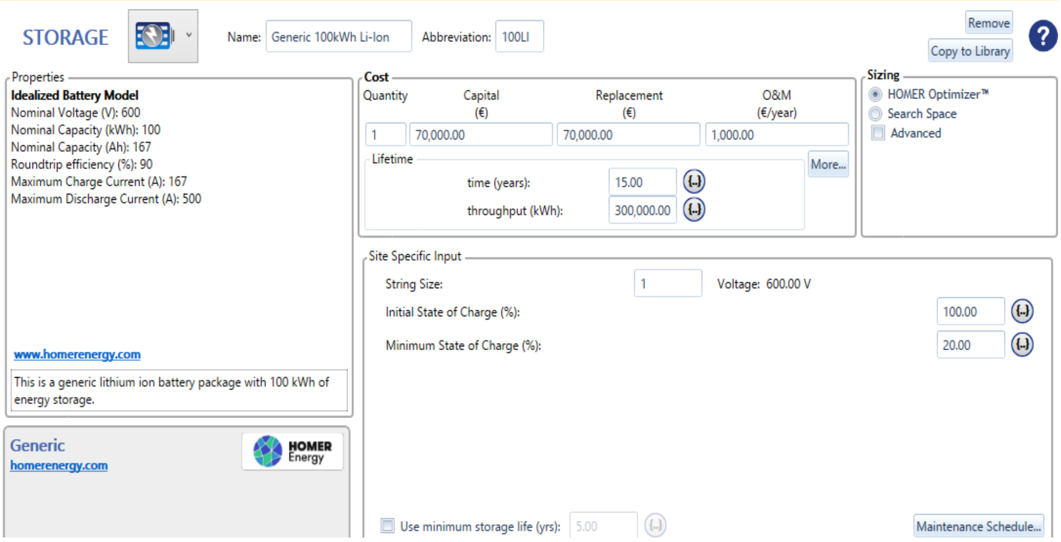
Renewable energy sources such as wind and solar photovoltaics are susceptible to fluctuations in supply (Jayawardana et al., 2019). The need for energy storage systems to handle volatility and intermittency is becoming increasingly evident as the world continues to transition to intermittent, renewable energy sources, such as solar and wind power (Dawood et al., 2020). In this study, a lithium-ion battery is selected as the storage component in the MESHS model 2 for the proposed EV charging station to store excess electricity generated. Lithium-ion batteries offer high energy density, efficiency, better performance, and fast response times (Kalliovalkama, 2024, p. 47). A 100% discharge is assumed since lithium-ion batteries may be depleted to zero (Das et al., 2021, p. 3). The battery has a 15-year lifespan. The battery capacity ($\mathrm{C_{bat}}$) can be calculated following equation (9) (Oladigbolu et al.,2023, p. 13).

$$\mathrm{C_{bat}} = \frac{\mathrm{E_{Load}} \times \mathrm{AD}}{\eta_{\mathrm{bat}} \times \mathrm{DOD} \times \eta_{\mathrm{inv}}} \tag{9}$$

Here, In the above $\mathrm{E_{Load}}$ is the daily energy load (kWh/day), AD defines the battery autonomy days, η_{inv} presents the inverter efficiency, DOD is the battery depth of discharge, and η_{bat} is the battery efficiency.

Equation (10) indicates the battery's state of charge ($\mathrm{SOC_b}$), which is expressed as a percentage (%) of the charge q_b to maximum charge q_{bm} ratio (Oladigbolu et al., 2023, p. 13).

$$\mathrm{SOC_b}\ (\%) = \frac{\mathrm{q_b}}{\mathrm{q_{bm}}} \times 100 \tag{10}$$



Name: Generic 100kWh Li-Ion
Abbreviation: 100LI

Properties
Idealized Battery Model
Nominal Voltage (V): 600
Nominal Capacity (kWh): 100
Nominal Capacity (Ah): 167
Roundtrip efficiency (%): 90
Maximum Charge Current (A): 167
Maximum Discharge Current (A): 500

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This is a generic lithium ion battery package with 100 kWh of energy storage.

Cost

Quantity	Capital (€)	Replacement (€)	O&M (€/year)
1	70,000.00	70,000.00	1,000.00

Lifetime
time (years): 15.00
throughput (kWh): 300,000.00

Sizing
● HOMER Optimizer™
○ Search Space
☐ Advanced

Site Specific Input
String Size: 1
Voltage: 600.00 V
Initial State of Charge (%): 100.00
Minimum State of Charge (%): 20.00
☐ Use minimum storage life (yrs): 5.00

Figure 15. Battery storage specification

The chosen 100kW Li-ion battery had unit capital and replacement costs of €70,000.00, and HOMER estimated that the annual operation and maintenance (O&M) expenses would be €1,000.00. It had a 300,000.00kWh throughput and a 15-year lifespan. The storage characteristics, technical details, and financial data of the chosen Li-ion battery are displayed in Figure 15 and Table 7 for the proposed multi-energy storage hybrid

Table 7. Technical and Economic properties of the lithium-ion battery storage

Properties	Value
Nominal Bus voltage	600 V
Nominal capacity (kWh)	100 kWh
Nominal capacity (Ah)	167 Ah
Roundtrip efficiency	90 %
Minimum State of charge	20 %
String Size	1 Battery
String in Parallel	1.00 strings
Lifetime throughput	300,000.00 kWh
Life span	15 years
Capital Cost (CAPEX)	€70,000.00 / qty.
Replacement Cost	€ 70,000.00 / qty.
Operation and Maintenance (O&M) Cost	€ 1,000.00/ year / qty.

Diesel Generator

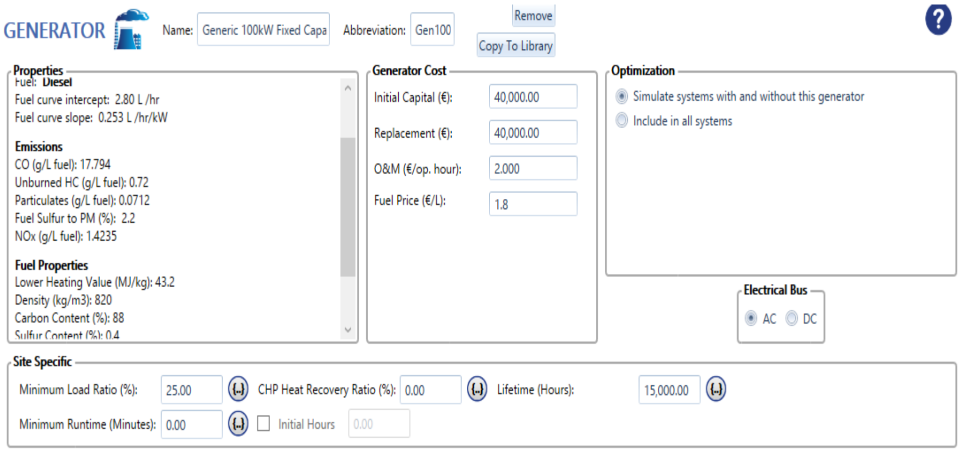
According to Das et al. (2021), the diesel generator consumes more fuel when operating at a lower load. In times of peak demand or power outages, diesel generators are used as a backup source of electricity (Bilal et al., 2024). Equation (11) may be used to determine the fuel consumption of diesel generators, represented as $\mathrm{F}_{\mathrm{DG,cons}}(\mathrm{t})$,

$$\mathrm{F}_{\mathrm{DG,cons}}(\mathrm{t}) = 0 \cdot 246 \times \mathrm{P}_{\mathrm{DG}}(\mathrm{t}) + 0.08415 \times \mathrm{P}_{\mathrm{rated-DG}} \tag{11}$$

The equation for the efficiency of the diesel generator as follows,

$$\eta_{\mathrm{overall}} = \eta_{\mathrm{brake\ thermal}} + \eta_{\mathrm{DG}} \tag{12}$$

In equation no. (11), $\mathrm{P}_{\mathrm{DG}}(t)$ is the power produced by the diesel generator (kW) at each instant t, $\mathrm{P}_{\mathrm{rated-DG}}$ is the rated power of the diesel generator, In equation (12) η_{overall} is the overall efficiency, $\eta_{\mathrm{brake\ thermal}}$ is the brake thermal efficiency, and η_{DG} defines the generator efficiency (Bilal et al., 2024, p. 7).



Name: Generic 100kW Fixed Capa
Abbreviation: Gen100

Fuel: **Diesel**
Fuel curve intercept: 2.80 L /hr
Fuel curve slope: 0.253 L /hr/kW

Emissions
CO (g/L fuel): 17.794
Unburned HC (g/L fuel): 0.72
Particulates (g/L fuel): 0.0712
Fuel Sulfur to PM (%): 2.2
NOx (g/L fuel): 1.4235

Fuel Properties
Lower Heating Value (MJ/kg): 43.2
Density (kg/m3): 820
Carbon Content (%): 88
Sulfur Content (%): 0.4

Initial Capital (€): 40,000.00
Replacement (€): 40,000.00
O&M (€/op. hour): 2.000
Fuel Price (€/L): 1.8

● Simulate systems with and without this generator
○ Include in all systems

● AC ○ DC

Minimum Load Ratio (%): 25.00
CHP Heat Recovery Ratio (%): 0.00
Lifetime (Hours): 15,000.00
Minimum Runtime (Minutes): 0.00
☐ Initial Hours 0.00

Figure 16. Diesel generator specification

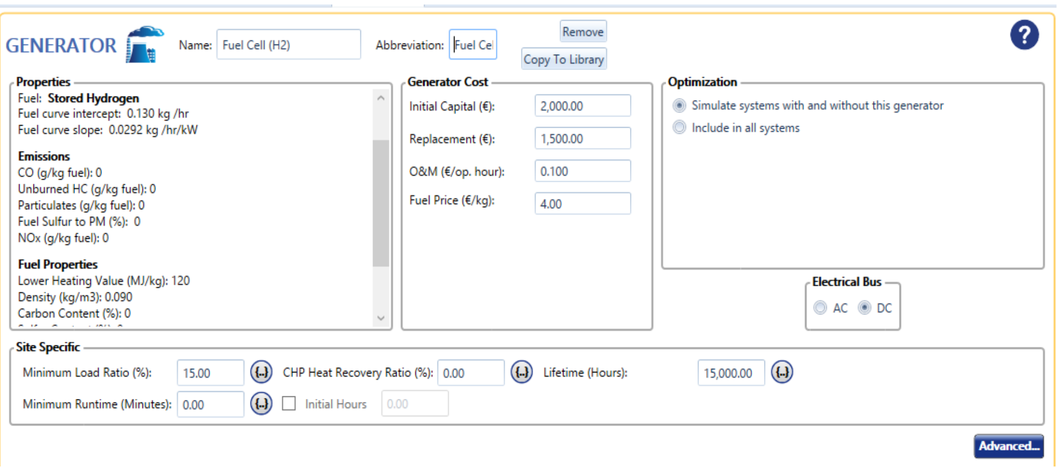
A generic 100 kW fixed generator, Gen100 (D), with a 25% minimum load ratio and connected to the AC electrical bus, is used in this research to serve as the backup power while renewable energy is intermittent. The fuel considered for this generator is diesel. HOMER Pro software has specified an initial capital cost of €40,000.00, a replacement cost of €40,000.00, and O&M costs of 2€/hour. HOMER provided a lifetime of 15,000 operating hours for this generic 100 kW fixed capacity generator. The diesel price varies, and the highest noted price was 2.519 €/L in July 2022 (mylpg.eu, 2025). During the peak month of January 2025, the diesel price in Finland was around 1.80 € per liter (StatFin, 2025; Global Petrol Prices, 2025). The sensitive cases also employed the assumption of varying diesel prices (1.70€/liter and 2.00€/liter) based on the last 5 years' prices in Finland. Table 8 presents important properties regarding the diesel generator.

Table. 8 Diesel generator properties and costs

Properties	Value
Generator power capacity	100 kW (fixed)
Fuel properties	Fuel: Diesel, Lower Heating Value (LHV): 43.2 (MJ/kg); Density: 820 (kg/m^3), Carbon content percent (88%)
Fuel curve interceptor	2.80 litre / hour
Fuel curve slope	0.253 lite/hour/kW
Fuel (Diesel) Prices (˜)	1.80 € / litre, 1.70€/litre, and 2.00€/litre
Initial capital cost (CAPEX)	40,000.00 €
replacement	40,000.00 €
O&M costs	2€ /hour
Lifetime	15,000 hours
Minimum load ratio	25 %

Fuel cells

HOMER Energy (n.d.-n) defines a fuel cell as a DC generator. The fuel cell will use the extra power that is electrolyzed to create hydrogen. A basic 100 kW fixed capacity generator was taken into consideration as a fuel cell that used extra power from an electrolysis process to directly make hydrogen (Das et al., 2021, p.3). A minimum load ratio of 15.00% was considered. The HOMER software assumed the lifetime of the fuel cell to be 15,000 hours. The price of green hydrogen fuel generated through the water electrolysis process varies from 4 to 8 €/kg in Finland (Järvinen, 2025). For this study, the fuel price is set as 4.00 €/kg. Technically, the stored hydrogen will be utilized, so HOMER's fuel price will be negligible. The initial capital cost of the fuel cell was assumed to be 2000 €/kW, the replacement cost was 1800 €/kW, and O&M costs of 0.01 €/kW/hr were used in this study (Figure 17.) (Al Badi et al., 2022, p. 06).



Name: Fuel Cell (H2)
Abbreviation: Fuel Ce

Properties
Fuel: **Stored Hydrogen**
Fuel curve intercept: 0.130 kg /hr
Fuel curve slope: 0.0292 kg /hr/kW

Emissions
CO (g/kg fuel): 0
Unburned HC (g/kg fuel): 0
Particulates (g/kg fuel): 0
Fuel Sulfur to PM (%): 0
NOx (g/kg fuel): 0

Fuel Properties
Lower Heating Value (MJ/kg): 120
Density (kg/m3): 0.090
Carbon Content (%): 0

Generator Cost
Initial Capital (€): 2,000.00
Replacement (€): 1,500.00
O&M (€/op. hour): 0.100
Fuel Price (€/kg): 4.00

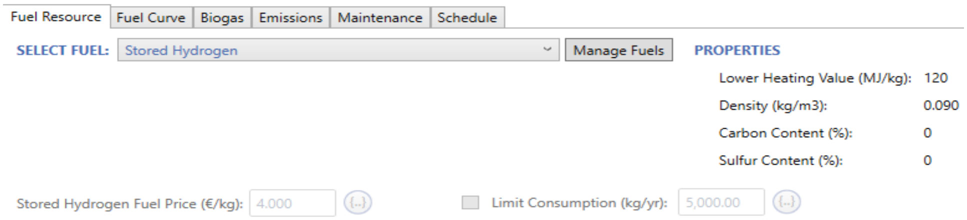
Optimization
● Simulate systems with and without this generator
○ Include in all systems

Electrical Bus
○ AC ● DC

Site Specific
Minimum Load Ratio (%): 15.00
CHP Heat Recovery Ratio (%): 0.00
Lifetime (Hours): 15,000.00
Minimum Runtime (Minutes): 0.00
☐ Initial Hours 0.00

Figure 17. Fuel Cell Configuration

When advanced fuel properties were configured, stored hydrogen was selected as the fuel specification. In Figure 18., the consumed fuel (stored hydrogen) has a density of 0.090 kg/m3 and a lower heating value of 120 MJ/kg.



SELECT FUEL: Stored Hydrogen

PROPERTIES
Lower Heating Value (MJ/kg): 120
Density (kg/m3): 0.090
Carbon Content (%): 0
Sulfur Content (%): 0

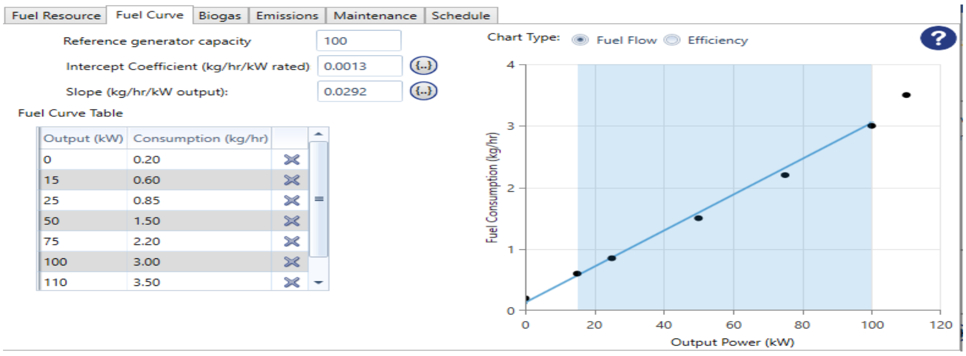
Stored Hydrogen Fuel Price (€/kg): 4.000
☐ Limit Consumption (kg/yr): 5,000.00

Figure 18. Resources and properties of the fuel cell

The fuel cell curve in Figure 19 presents the rated interception coefficient of the used fuel (stored hydrogen), 0.0013 kg/hr/kW. This demonstrated minimal idle fuel consumption. The fuel curve slope output is 0.0292 kg/hr/kW, which describes 0.0292 kg of fuel consumed per hour at every kW of energy output. The data calculated to find the fuel curve of the 100-kW generator following HOMER equation (13) (UL Renewables, n.d.-a).

$$\mathrm{F} = \mathrm{F}_0 \times \mathrm{Y}_{\mathrm{gen}} + \mathrm{F}_1 \times \mathrm{P}_{\mathrm{gen}} \tag{13}$$

In the above fuel curve slope equation (13), F is the fuel consumption (kg/hr), F_0 is the fuel consumed at zero output (intercept coefficient), F_1 is the slope (additional fuel consumed per kW of electrical output), Ygen defines the rated capacity of the generator (kW) and P_{gen} presents the actual electrical output this timestep.



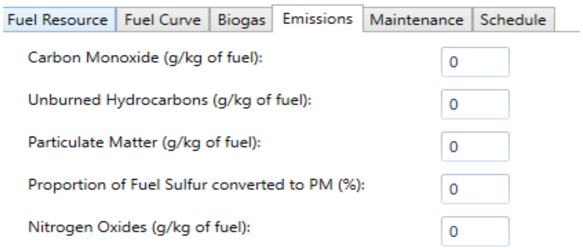
Reference generator capacity: 100
Intercept Coefficient (kg/hr/kW rated): 0.0013
Slope (kg/hr/kW output): 0.0292

Fuel Curve Table

Output (kW)	Consumption (kg/hr)
0	0.20
15	0.60
25	0.85
50	1.50
75	2.20
100	3.00
110	3.50

Figure 19. Fuel curve properties the fuel cell

When configuring the fuel cell generator with stored hydrogen, the emission components in Figure 19 were considered as 0 per g or kg of fuel, as the electricity generated by renewable sources produces near-zero or a very negligible amount of GHG emission (Zhao et al., 2021, p. 5).

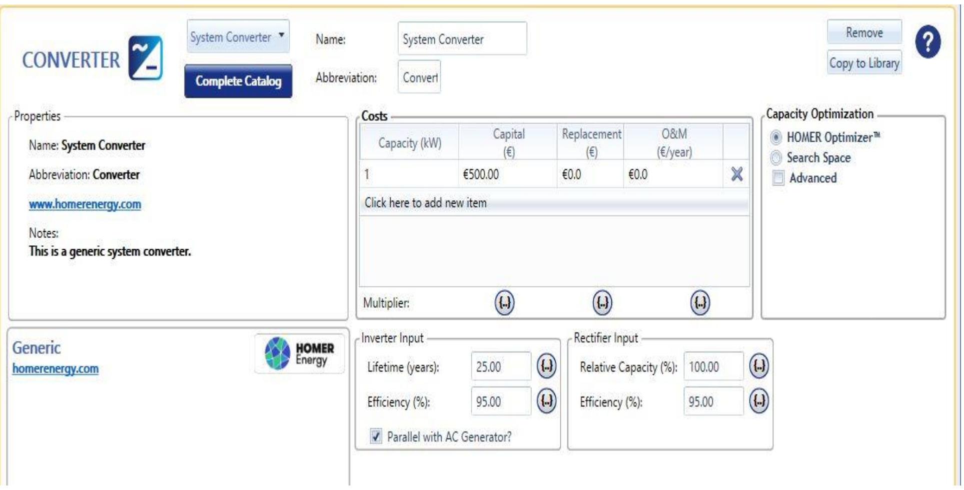


Carbon Monoxide (g/kg of fuel): 0
Unburned Hydrocarbons (g/kg of fuel): 0
Particulate Matter (g/kg of fuel): 0
Proportion of Fuel Sulfur converted to PM (%): 0
Nitrogen Oxides (g/kg of fuel): 0

Figure 20. Emission by the fuel cell (stored hydrogen)

Converters

A minimum of one converter is required for a microgrid system that includes both AC and DC components. Converter parameters depend on the selected type, which may include inputs for the inverter and rectifier, costs, and capacity optimization. The inverter converts electricity from DC to AC, while the rectifier converts from AC to DC. The inverter and rectifier parameters include lifetime, efficiencies, relative capacities, and whether the converter operates in parallel with an AC generator. The effectiveness of power conversion from one source to another is shown by the efficiency of the rectifier and inverter. The relative capacity of the rectifier is the difference between its rated capacity and the capacity of the inverter (HOMER Energy, n.d.-l; cited in Kalliovalkama, 2024, p. 46).



Name: System Converter

Abbreviation: Convert

Properties

Name: System Converter

Abbreviation: Converter

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Notes:
This is a generic system converter.

Costs

Capacity (kW)	Capital (€)	Replacement (€)	O&M (€/year)
1	€500.00	€0.0	€0.0

Click here to add new item

Multiplier:

Capacity Optimization

● HOMER Optimizer™

○ Search Space

☐ Advanced

Inverter Input

Lifetime (years): 25.00

Efficiency (%): 95.00

☑ Parallel with AC Generator?

Rectifier Input

Relative Capacity (%): 100.00

Efficiency (%): 95.00

Figure 21. Converter configuration

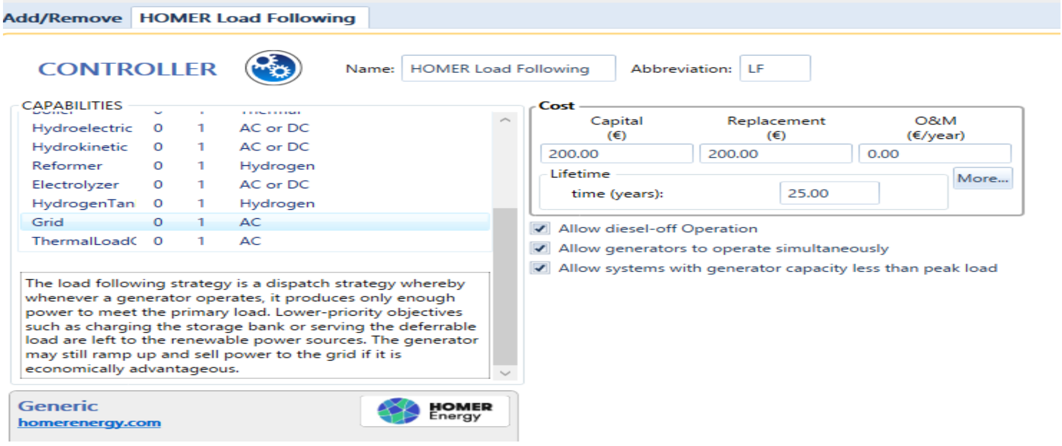
The general system converter's capital cost is estimated to be €5,00.00/kW (Figure 21.) neither replacement nor operating and maintenance costs are taken into account (Al Badi et al., 2022, p. 6). The lifespan of the converter is 25 years. The HOMER optimizer maximizes the converter's capacity (Rong et al., 2025, p. 843). The following equation (14) might be used to get the converter capacity (C) (Oladigbolu et al. 2023, P.13).

$$\mathrm{C} = (3\ \times \mathrm{L_i}) + \mathrm{L_r} \tag{14}$$

Here, $\mathrm{L_i}$ denotes the inductive and $\mathrm{L_r}$ resistive loads. The HOMER pro software determined the relative capacity (C) 100% and 95% efficiency of the rectifier and inverter for the generic system converter, as shown in Figure 21.

Controller- Load Following (LF)

The proposed MESHS integrated EV charging station (off-grid) utilized HOMER's generic load-following controller. The load following (LF) controller generates power to support the principal load, as stated in HOMER Pro Software (Figure 22). A multi-energy-based hybrid system uses renewable energy sources to power other deferrable loads or charge the storage. Checking "allow diesel-off operation" in the controller, keeps the system stable while the generator is off. Checking the "allow generators to operate simultaneously" box only impacts systems with multiple generators on the same bus. When needed, HOMER lets multiple generators on a bus run simultaneously. Without it, generators on the same bus must operate individually. Finally, choosing "allow systems with generator capacity less than peak load" allows HOMER to recommend a generator below peak load if alternative sources like batteries or fuel cell can better meet that load. If this option is unchecked under the "allow systems with generator capacity less than peak load," HOMER will deem a generator below peak infeasible (HOMER Energy, n. d. -o). The basic LF controller costs €200 for both purchases and replaces it over its 25-year lifespan.



Name: HOMER Load Following

Abbreviation: LF

Hydroelectric	0	1	AC or DC
Hydrokinetic	0	1	AC or DC
Reformer	0	1	Hydrogen
Electrolyzer	0	1	AC or DC
HydrogenTan	0	1	Hydrogen
Grid	0	1	AC
ThermalLoad(	0	1	AC

The load following strategy is a dispatch strategy whereby whenever a generator operates, it produces only enough power to meet the primary load. Lower-priority objectives such as charging the storage bank or serving the deferrable load are left to the renewable power sources. The generator may still ramp up and sell power to the grid if it is economically advantageous.

Cost

Capital (€)	Replacement (€)	O&M (€/year)
200.00	200.00	0.00

Lifetime

time (years): 25.00

☑ Allow diesel-off Operation

☑ Allow generators to operate simultaneously

☑ Allow systems with generator capacity less than peak load

Figure 22. Controller for the proposed MESHS optimization

3.7 Reliability and Validity of Research

According to Bryman and Bell (2007), validity and reliability are metrics used to evaluate the trustworthiness of research projects. Reliability can only be estimated; it cannot be calculated according to the fundamental theory of reliability. To estimate reliability, several methods are needed. Although validity and reliability are seen as distinct ideas, they are part of an interconnected system. In the case of validity, the concepts and techniques of measurement are different, but in the case of reliability, they are the same. Furthermore, it is crucial for research projects to integrate the concept of reliability with the other essential requirements for evaluating validity and to comprehend the connections between validity and reliability in measurement (Trochim, 2020; Badhan, 2020, p. 13). Validity, according to Ghauri and Gronhaug (2005), is the degree to which the data gathered accurately reflects the field of study. One method for evaluating the validity of data is triangulation, which involves comparing the data collected from several sources, techniques, or theories (Ediyanto et al., 2025). In a study using the emergent design and descriptive qualitative approach, triangulation can be conducted (Chen, 2018; Ediyanto et al., 2025, p. 165). Research that frequently employs a particular approach may have flaws that reduce the validity of its outcomes. To enhance data collection and validate research findings, triangulation is addressed for studies that employ various research approaches (Zuze and Weideman, 2013; Ediyanto et al., 2025, p. 166). Researchers use triangulation to expand the scope of data collection and increase the chances of observing a variable from multiple viewpoints (Muhammad, 2020; Ediyanto et al., 2025, p. 167). The most significant aspect of triangulation is to ensure the reliability and validity of the results. Data triangulation reduces measurement bias results from the various data collection methods (Odiri, 2019; Ediyanto et al., 2025, p. 167).

The strategies for conducting the survey were clearly explained. The questionnaires were created solely by the researcher, but they were reviewed by the supervisor before distribution. The survey questionnaire model was developed with the help of the Microsoft Form link, which also guaranteed that the researcher's identity and goal were communicated effectively to the targeted participants, including experts and various stakeholders in the energy field. Instead of using other random online tools, the respondents felt safe and were more interested in participating through Microsoft Forms, leading to more reliable data collection.

For a case study, triangulation is a suitable recommended methodology that is known to produce reliable data, conclusions, and convergent methodologies (Farquhar et al., 2020; Ediyanto et al., 2025, p. 166). The case study incorporates optimization, simulation, and sensitivity analysis. In the case study, two distinct hybrid energy storage models were optimized for the Arctic region's EV charging station, based on the survey's two top-ranked storage options. The popular energy modeling software, HOMER Pro, was utilized to simulate the data obtained from energy experts, engineers, researchers, and various other stakeholders. Therefore, a solid basis of validity was established for the study by evaluating the information provided by energy experts and other stakeholders through the survey and simulation.

4 Results and Analysis

In this section, the survey and case study findings are presented and analyzed.

4.1 Survey Outcomes and Interpretation

Considering the research objective, this section provides a thematic interpretation of the survey outcomes, which include assessments of cost factors, technical feasibility, environmental impact, social/community factors, and policy measures. Additionally, the analysis of the open feedback is also outlined.

Cost Factor Assessment

Regarding the initial investment (CAPEX) in renewable energy-based EV charging infrastructure, most of the stakeholders, about 44%, indicated high cost, 9% indicated extreme costs, and 41% mentioned a moderate cost compared to diesel-based systems. Only 6% of the stakeholders mentioned low costs, and no one considered the initial capital expenses very low (0%). The CAPEX assumed by the participating stakeholders is represented in Figure 23.

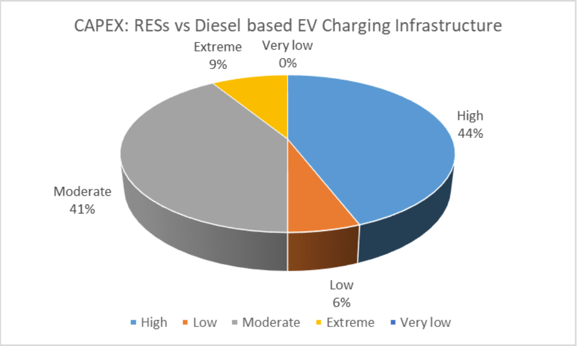


Figure 23. CAPEX for the RESs vs Diesel-based EV charging station

When perceiving the operational and maintenance cost-effectiveness illustrated in Figure 24, the highest number of participants (41%) considered renewable energy-based EV charging solutions as cost-effective, and 26% defined them as more cost-effective. However, 12% of the participants considered it to be less cost-effective, and 21% selected it as comparable with the diesel-based EV charging infrastructure.

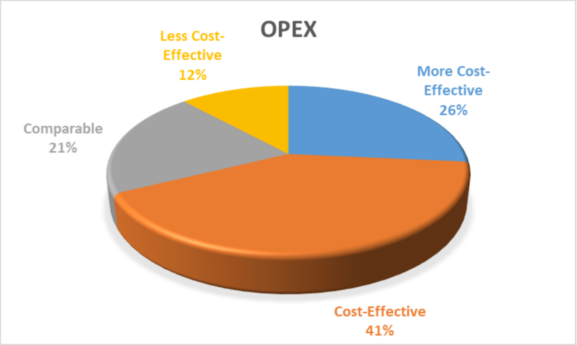


Figure 24. OPEX of the RESs vs Diesel-based EV charging station

Assuming the life cycle cost (LCC) or total net present cost (NPC) of RES-based multi-energy-storage hybrid systems depicted in Figure 25, the majority of 49% considered them cost-effective and viable, 39% thought the cost would vary, and 12% considered them very costly and non-viable compared to the traditional fossil fuel (diesel)-based systems for an EV charging station.

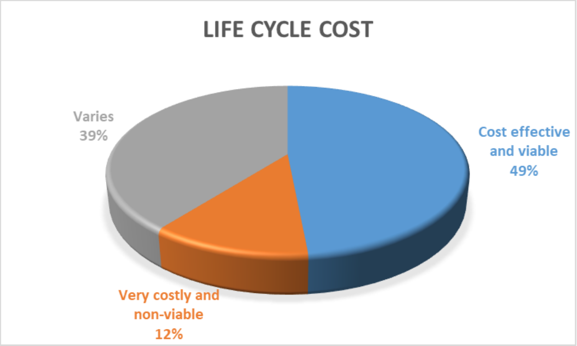


Figure 25. Life cycle cost of the RESs vs a diesel-based EV charging station

When estimating the levelized costs of energy (LCOE) for RES-based multi-energy-storage hybrid systems presented in Figure 26. 35% considered the price comparable, 26% considered it lower, and 3% considered the levelized cost significantly lower than the traditional fossil fuel (diesel) based systems. In contrast 21% highlighted the levelized cost of the multi-energy storage hybrid systems (MESHS) as higher, and 15% considered a significantly higher levelized cost in comparison with the traditional diesel-based energy system for Arctic EV charging.

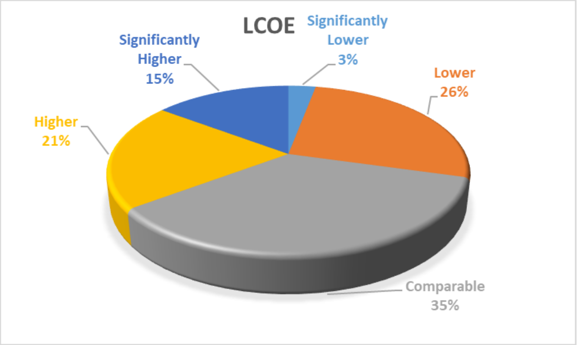


Figure 26. Levelized costs of energy (LCOE) of the RESs vs Diesel-based EV charging station

When estimating the levelized cost of storage (LCOS), as in Figure 27, for RES-based multi-energy-storage hybrid systems, 41% indicated price variation, 35% directly highlighted higher costs, 3% equal, and 21% considered lower compared to the traditional fossil fuel (diesel)-based systems.

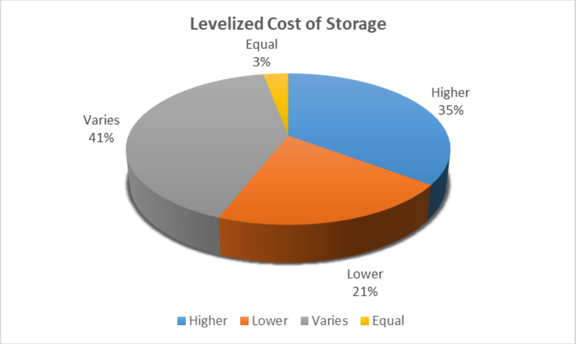


Figure 27. Levelized cost of storage for RESs vs Diesel-based EV charging station

Thereby, multiple important factors (in Figure 28) were considered for evaluating the feasibility of charging solutions for EVs in the remote Arctic areas. The highest number (21) emphasized the initial capital cost, followed by the energy storage efficiency (20), renewable source abundance (17), maintenance cost (15), and grid independence (14). A smaller number (9) also considered government incentives as an important factor to ensure the feasibility of the Arctic EV charging solution.

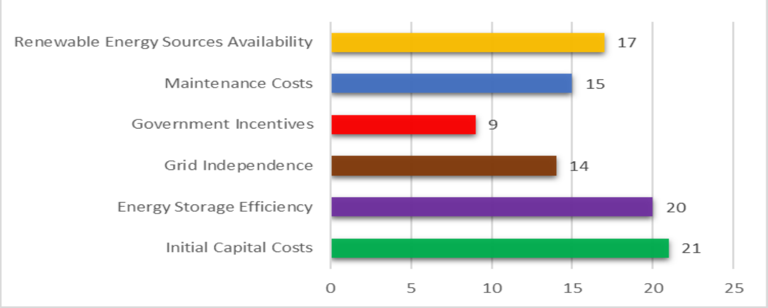


Figure 28. Important factors of the RESs vs Diesel-based EV charging station

Around 16 participants (25%) highlighted (in Figure 29) that the high upfront costs, funding or investment, and unpredictable return on investment (ROI) are the financial barriers in deploying a multi-energy storage hybrid system (MESHS) in remote Arctic communities. Some nine participants (14%) also indicated maintenance complexity, and a few, about 7 people (11%), mentioned the lack of skilled personnel as a barrier due to economic factors for deploying the MESHS-based EV charging in remote areas.

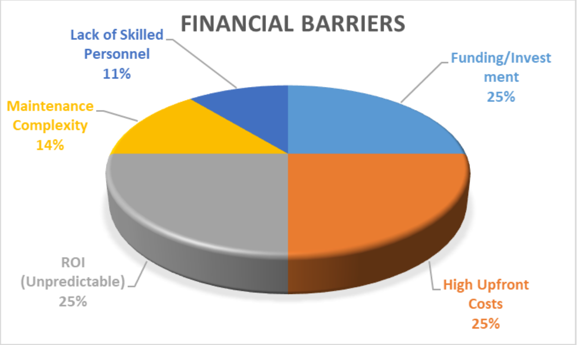


Figure 29. Potential Financial Barriers

Technical Feasibility

While assessing technical feasibility, eighteen of the participants (53%) emphasized the importance, and eight of them (26%) considered it somewhat important to integrate the renewable energy sources with EV charging infrastructure in Arctic regions. Considering the suitable renewable sources for the proposed MESHS for EV charging in the Arctic region, wind resulted in the highest rank (42%), followed by hydropower (22%) and solar PV (17%). The other renewable sources were identified as geothermal (10%), with a very low ranking for biomass (9%) energy, as depicted in Figure 30.

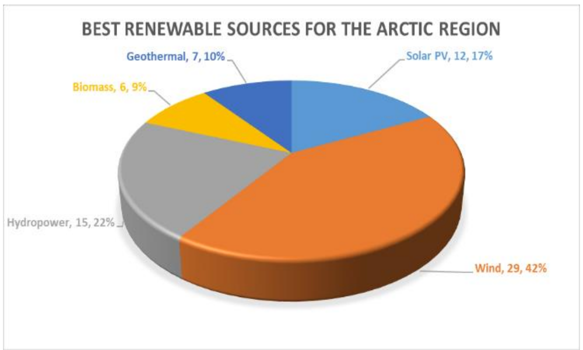


Figure 30. RESs for the Arctic region

A maximum of 56% of participants emphasized the importance of the role of energy storage systems such as batteries, thermal storage, and hydrogen storage in the success of EV charging infrastructure, except that only 3% of participants did not consider the importance, resulting in a lack of knowledge regarding the energy storage system. The two most reliable energy storage technologies recommended by the participants were the hydrogen fuel cell (35%) and the lithium-ion battery (32%). Some 14% suggested flywheel storage, and 11% mentioned thermal storage would be the most reliable energy storage for Arctic EV charging. Additionally, some 8% indicated other storage technologies like sodium-ion batteries.

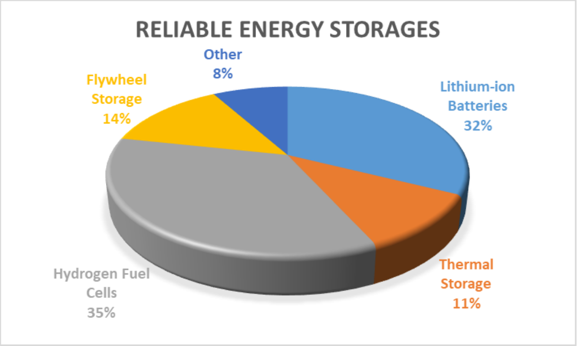


Figure 31. Reliable energy storage technologies for Arctic EV charging

Hydrogen storage technology presented immense potential for Arctic conditions (Figure 31). For assuring effectiveness while optimizing the hydrogen storage, it is emphasized as essential by the participants to consider better insulation for the storage tank (25%), a cost-effective electrolyzer (24%), and cold-resistant fuel cells (22%). Consideration should also be taken for effective transportation (22%) and advanced safety protocols (6%).

Environmental Impact Assessment

The participants showed various levels of concern regarding several environmental aspects of the multi-energy systems. Particularly, 36% presented extreme concern about carbon emissions from traditional or diesel-based EV charging systems, while 27% showed high concern, 21% rated normal concern, 6% indicated moderate concern, and 9% recognized least concern. They also rated the impacts as 18% extreme, 39% high, 33% normal, and 9% moderate, associated with battery production/mining in the Arctic region. Additionally, they identified the risks with hydrogen leakage as 3% at least, 55% normal, 9% moderate, 24% high, and 9% extreme concern, resulting in normal risks for hydrogen leakage in the Arctic.

Another environmental impact that involves the land use for renewable infrastructure in the Arctic was identified by the participants as 3% least concern, 16% moderate, 39% normal, 29% high, and 13% extreme concern.

Noise from wind turbines in the Arctic presented 27% least concern, 15% moderate, and 21% normal concern. However, 30% of the participants considered the noise to be of high concern, while 6% rated it as extreme concern.

The factors associated with end-of-life disposal of storage systems in the Arctic were ranked by the participants as 12% extreme, 35% high, 32% normal, 12% moderate, and 9% least concern.

Seventeen (50%) participants significantly indicated these multi-energy storage hybrid systems (MESHS) as somewhat important, and thirteen (38%) considered them critical in reducing dependence on fossil fuels in Arctic regions. However, one participant (3%) considered the multi-energy storage hybrid (MESHS) extremely unimportant, while three participants (9%) chose a neutral stance.

The majority of the participants, 47% (sixteen), believed that MESHS-based EV charging solutions could significantly reduce carbon emissions in Arctic conditions. In addition, 26% (nine) of individuals somewhat agreed with the fact, and 15% (five) remained neutral. However, only 12% (four) gave a negative response.

On the aspect of life cycle assessment (LCA), about 44% (fifteen participants) strongly agreed, along with 29% (ten participants), which could measure and help reduce the environmental factors related to such EV-charging projects with multi-energy storage systems. About 24% (eight participants) were neutral about the LCA, and 3% (one individual) disagreed.

Social/Community-Related Factors

Seventeen participants (50%) considered community involvement to be somewhat important, while nine of them (26%) recognized it as critical when designing multi-energy storage hybrid systems (MESHS) for Arctic EV charging. In addition to that, some seven participants (21%) gave a neutral opinion on that aspect, while one (3%) found the community involvement not relevant.

The social barriers that may hinder the deployment of grid-independent and highly renewable energy-based vehicle charging infrastructure and EV adoption in the Arctic communities were explored, and the results are presented in Figure 32. The most significant impact identified was the shortage of charging infrastructure (according to 15 participants), followed by very high initial costs for the new vehicles (mentioned by 7 participants), shortage of daylight in winter (5 participants recognized), and anxiety about extreme cold weather (4 participants marked). Other identified barriers are cultural resistance to new technology (2 participants) and lack of awareness of benefits (1 participant), which might also affect the EV adoption within the Arctic community.

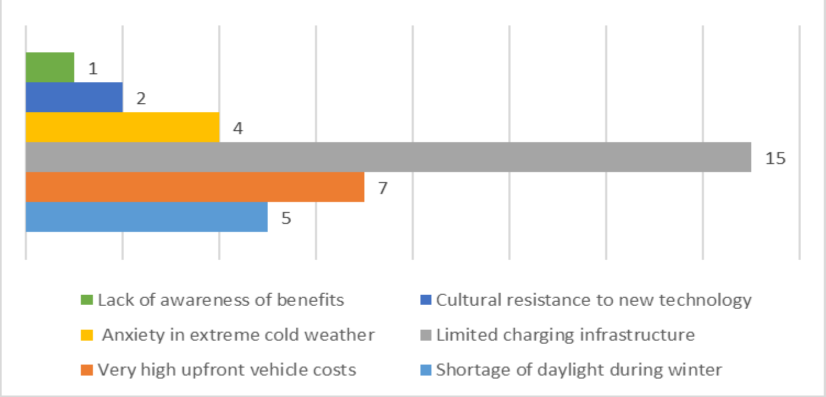


Figure 32 Potential social barriers hinder EV charging deployment and EV adoption in Arctic communities.

Again, the factors that may negatively affect the broader uptake of EV adoption in the Arctic region are insufficient charging infrastructure (mentioned by 32%), a limited driving range (24%), concerns about storage life and availability (23%), and high upfront cost (marked by 21%).

Participants' experiences were also explored by inquiring about their dependency on the hybrid renewable energy systems. To continuously power EVs in Arctic winters, 65% of participants (22 individuals) indicated that they could somewhat depend on the hybrid renewable energy systems, while 6% (2 participants) stated they could completely depend on them. Additionally, 15% (5 participants) were neutral, and the remaining 15% (5 participants) reported that they cannot depend on these systems.

Policy Measure

Only 2 participants (6%) rated government support for renewable energy projects in the Arctic region as poor, while an average rating was given by the highest number of participants, 18 (55%). In contrast, 10 participants (30%) considered the existing government incentives as good, while 3 of them (9%) supported them as excellent.

The survey identified that tax incentives (33%) and carbon pricing (28%) offer the highest potential policy measures that could enhance multi-energy storage hybrid systems (MESHS) deployment in the study region. Additional grants for such energy pilot projects (22%) and cross-border collaboration (17%) could also have a positive impact. Reducing imports and using or achieving complete independence from fossil fuels like diesel in the Arctic region, however, was found critical by 44% (15 participants). Moreover, 29%

(10 participants) considered this factor extremely critical. In the meantime, 21% (7 participants) were neutral, and 6% (2 participants) recognized it as non-critical.

Qualitative Insights

An open feedback option was included with the survey questionnaires. Some five participants shared their views. Four of the feedback responses provided important insights relevant to the research, while one feedback was found not necessary for the result analysis.

One anonymous participant suggested that sodium batteries could be better energy technology. One of the participants proposed that a liquid hydrogen storage system combined with solar PV and wind turbines could be a better solution for EV charging in the Arctic region. Another participant commented as

“Reducing carbon emissions is a behemoth of a task.”

He highlighted the global urgency of carbon neutrality, multilateral cooperation, and new disruptive technologies. He pointed out that a couple of new carbon-neutral energy technologies offered by some countries are not ideal, but still, he suggested adopting the technologies globally. The importance of raising awareness among country leaders and citizens is equally important, according to him. He further stressed the idea that every single person contributing to carbon neutrality is important.

One participant commented,

“I am strongly supporting EV adoption in Nordic countries for the sake of Mother Earth.”

The fifth piece of feedback consisted of a generic comment about the survey design, the questionnaire pattern, and suggestions for improvements. This feedback was deemed unnecessary for the analysis and was therefore neglected.

In sum, the quantitative survey explored the cost factors, technical viability, and environmental concerns from the stakeholder's perspective regarding the multi-energy storage system for EV charging in the Arctic region. In addition, the survey explored the policy measures and social aspects relevant to such energy projects. The findings provide valuable insights regarding renewable energy sources and energy storage technologies. Wind, hydropower, and solar PV ranked as the top renewable sources, while hydrogen storage with fuel cells and lithium-ion batteries were rated as suitable for the study location by the stakeholders. The surveys highlighted critical concerns, including high capital investment, a shortage of infrastructure, the need for better insulation in storage, and carbon emission reduction. Additionally, the survey suggested communities' involvement in charging station design, life cycle impact assessment, and advocating policy measures like tax incentives, carbon pricing, etc. Furthermore, the survey analyzed the qualitative feedback given by the stakeholders and tried to obtain unique information that mitigates the limitation of the survey design with closed-end questionnaires. The survey findings further supported the case study analysis through a simulation and evaluation of the research objective in this study.

4.2 Case Study Results - Simulation and Feasibility Assessment

In this part of the case study, the simulation results and feasibility assessment (HOMER Pro) software for the two multi-energy storage hybrid systems (MESHS) models, MESHS Model 1 with hydrogen (H_2) and MESHS Model 2 with lithium-ion battery technology for the EV charging infrastructure at Utsjoki, Finland, are presented and analyzed.

4.2.1 Simulation Results for the MESHS Model 1 (with H_2 Storage)

a) System Overview

This hybrid multi-energy storage system (MESHS model 1) in Figure 33 is designed for off-grid EV charging in Utsjoki, Finland. The main configuration components of the MESHS model include a wind turbine, solar PV, a diesel generator (Gen100(D)), an electrolyzer, a hydrogen storage tank (HTank), a fuel cell, and a generic converter (AC-DC).

An additional hydrogen load was provided by external hydrogen generation, which utilizes excess electricity or energy generated by this hybrid energy storage system. Considering the requirements of the HOMER Pro software, a load-following controller is utilized. It applies the same capacity factors to both energy sources (solar and wind energy) in the same location and employs the optimizer (Kalliovalkama, 2024, p. 90). The estimated EVCS load was considered 600 kWh/day, with a peak load of 99.44 kW and a load factor of 0.25. The project lifetime considered was 25.0 years.

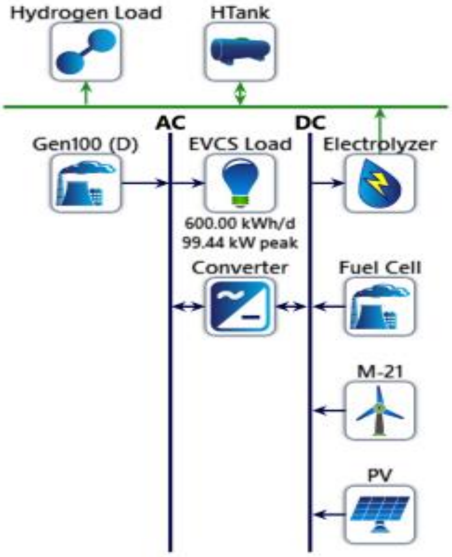
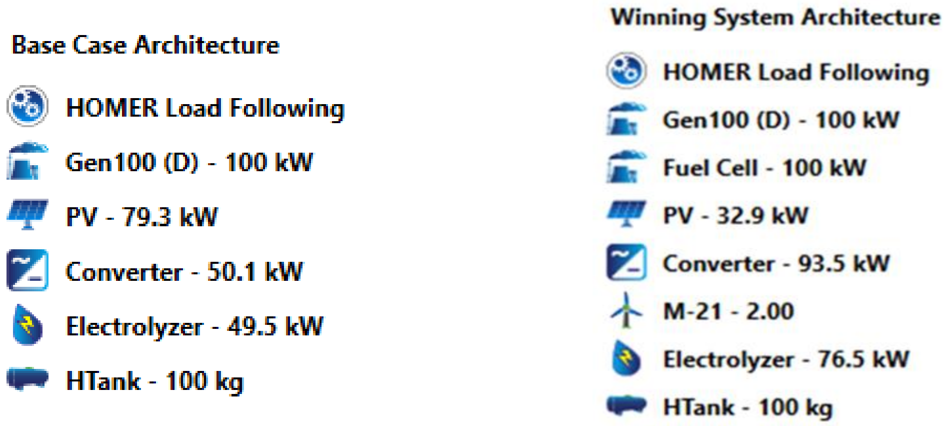


Figure 33. Schematic diagram of the optimized MESHS model 1 (with H_2 storage)

b) Optimization Outcome



Base Case Architecture

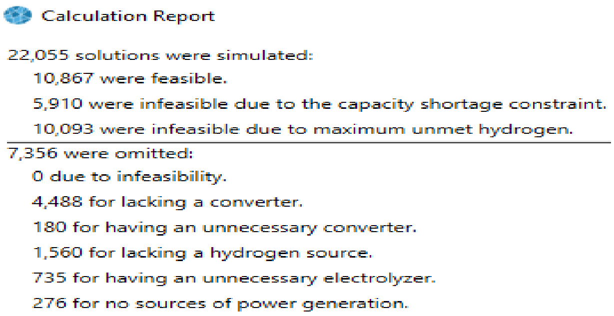
- HOMER Load Following
- Gen100 (D) - 100 kW
- PV - 79.3 kW
- Converter - 50.1 kW
- Electrolyzer - 49.5 kW
- HTank - 100 kg

Winning System Architecture

- HOMER Load Following
- Gen100 (D) - 100 kW
- Fuel Cell - 100 kW
- PV - 32.9 kW
- Converter - 93.5 kW
- M-21 - 2.00
- Electrolyzer - 76.5 kW
- HTank - 100 kg

Figure 34. System Architecture for the MESHS model 1 (Base Case & Winning System) (HOMER Pro)

From the optimization of the MESHS Model 1 with H_2 storage at 600kWh/day EVCS load and a diesel price € 1.80, the winning system and base case system resulted in the components illustrated in Figure 34. The base system included PV (79.3 kW), a 100-kW diesel genset, a converter (50.1 kW), an electrolyzer (49.5 kW), a hydrogen storage tank (100 kg), and a controller (LF) (HOMER Pro). On the other hand, the winning system combines a PV (32.9 kW), a WT (2.00 of 100 kW), a 100-kW diesel generator [Gen100 (D)], a converter (93.5 kW), an electrolyzer (76.5 kW), a hydrogen storage tank (HTank) (100 kg), a 100 kW fuel cell (H_2), and a controller (HOMER load following).



```
22,055 solutions were simulated:
    10,867 were feasible.
    5,910 were infeasible due to the capacity shortage constraint.
    10,093 were infeasible due to maximum unmet hydrogen.
7,356 were omitted:
    0 due to infeasibility.
    4,488 for lacking a converter.
    180 for having an unnecessary converter.
    1,560 for lacking a hydrogen source.
    735 for having an unnecessary electrolyzer.
    276 for no sources of power generation.
```

Figure 35. Calculation report for MESHS model 1 (HOMER Pro)

The optimized model calculated 22,055 solutions during simulation, where the reported feasible solutions number was 10,867. On the other hand, 5,910 reported infeasible solutions were due to the constraints of capacity shortage, and 10,093 were infeasible due to maximum unmet hydrogen load (Figure 35).

c) Optimized Component Properties

Wind Turbine (100 kW): The rated capacity of the XANT M-21 wind turbine was 200 kW (2 units), as shown in Figure 36. The annual energy production was 646,720 kWh, which was 85.6% of total generation. The capacity factor was 36.9%, and wind penetration was 295%, which presented good capacity for the Arctic region. Total hours of operation: 7,602 hrs/year. The life cycle cost, or total NPC, was €347,918.27, and the levelized cost was €0.0416/kWh.

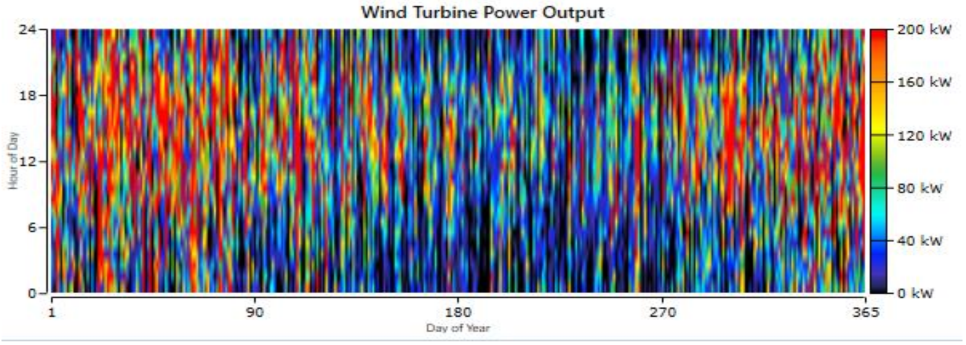


Figure 36. WT [XANT M-21 (100 kW)] output of MESHS model 1 (HOMER Pro)

Solar PV (32.9 kW): The rated capacity of the selected solar photovoltaic panel (SunPower E20-327) was 32.9 kW at the average electrical load demand of the EV station, 600kWh/day. The PV power output is illustrated in Figure 37. The mean average output of this PV panel was 80.7 kWh/day, and the maximum output was 33.2 kW. Total hours of operation by the PV system were 4,379 hours/year. The lower value of the capacity factors, 10.2% of the photovoltaic output, was presented in the Arctic winter darkness and short daylight situation, and the penetration of the PV system was 13.5%. This PV panel's total annual energy production was 29,461 kWh/year, a mere 3.90% of the total energy production of the proposed system.

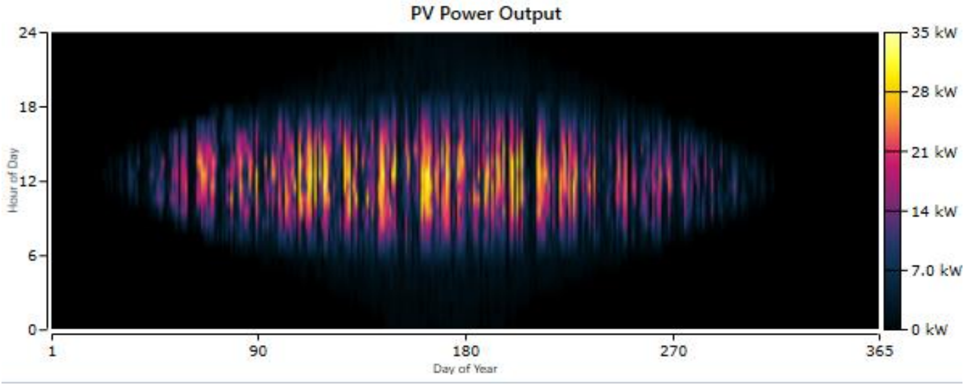


Figure 37. Solar PV output of MESHS model 1 (HOMER Pro)

Diesel Generator [Gen100 (D)]: A generic 100kW (fixed capacity) generator, Gen100 (D), was used in the proposed MESHS model 1. The annual energy production capacity of this diesel genset was 4,578 kWh/year, which was around 0.606% of the total energy production. Fuel consumption for the genset is 1,612 L/ year (backup for emergencies).

Hours of operation were 162 hrs/year, capacity factor was 0.523%, and efficiency was 28.9%. The specific fuel consumption is 0.352 L/kWh, and the marginal generation cost is €0.455/kWh. Generator power output is illustrated in Figure 38.

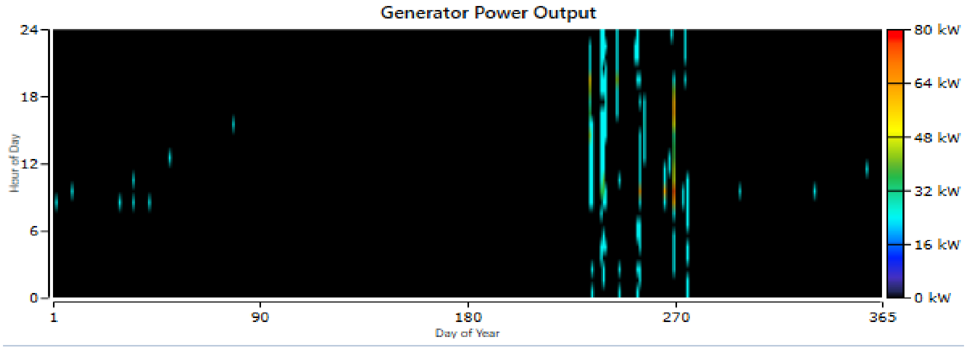


Figure 38. Gen100 (D) Power Output for MESHS Model 1 (HOMER Pro)

Hydrogen Module

The hydrogen module comprises a 76.5 kW rated capacity electrolyzer, a 100 kg hydrogen storage tank (HTank), a 100 kW generator as a fuel cell (H_2), and a hydrogen load (5kg/day). The levelized cost of hydrogen, LCOH, is €12.9/kg, which is much higher than the levelized cost of energy (LCOE) of €0.269/kWh of the system.

Electrolyzer: The H_2 production capacity of the electrolyzer was 4,565 kg/year. The specific consumption of the electrolyzer was 60.7 kWh/kg. The capacity factor of the electrolyzer was found to be 41.4%, presenting a high rate. Figure 39 and Figure 40 illustrate the daily input power and monthly output of the electrolyzer.

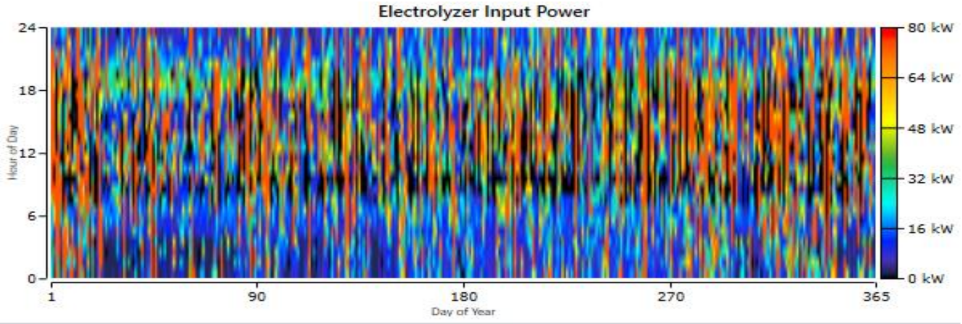


Figure 39. Electrolyzer input power (daily) (HOMER Pro)

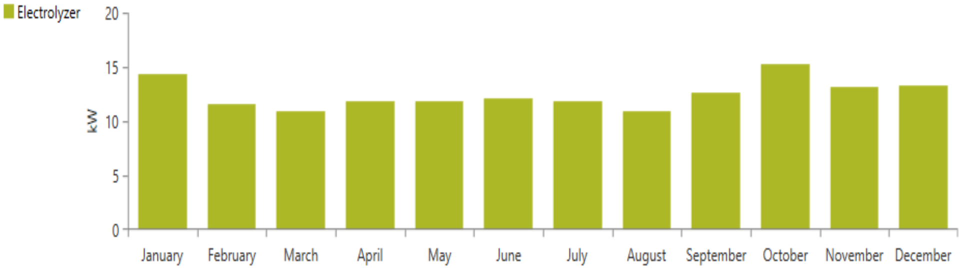


Figure 40. Electrolyzer output power (monthly) (HOMER Pro)

The excess hydrogen and unmet hydrogen were found to be zero, which demonstrated the reliability of the electrolyzer. The electricity consumption by the electrolyzer is 277,013 kWh/year, which is 55.8% of the total electricity consumption from the system.

Hydrogen Fuel Cell (100 kW): The rated capacity of the fuel cell (H_2) is 100 kW. The annual energy production capability is 74,745 kWh (9.89% of total energy production). The mean electrical efficiency measured 83.4%, which indicated very high efficiency. The capacity factor is 8.53%. Total operation time: 3912 hrs/year. Total H_2 consumption was found to be 2,690 kg/year, which was 59.6% of the total hydrogen consumption by the system. The present net cost (NPC) of the fuel cell is €12,223.91 (NPC); the marginal generation costs €0/kWh, since the fuel cell was designed to use the stored hydrogen. Power output from the fuel cell is illustrated in Figure 41.

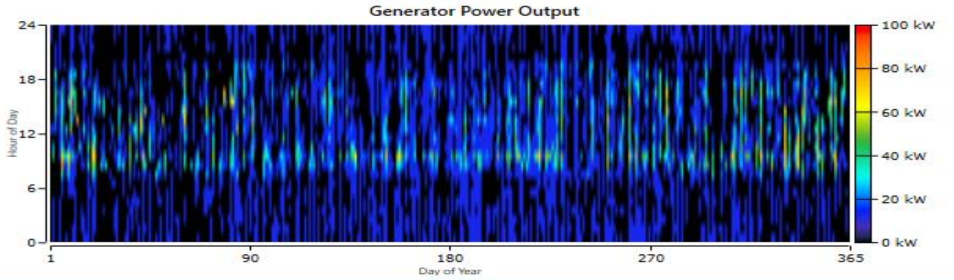


Figure 41. Power output of the Hydrogen Fuel Cell (100kW capacity) (HOMER Pro)

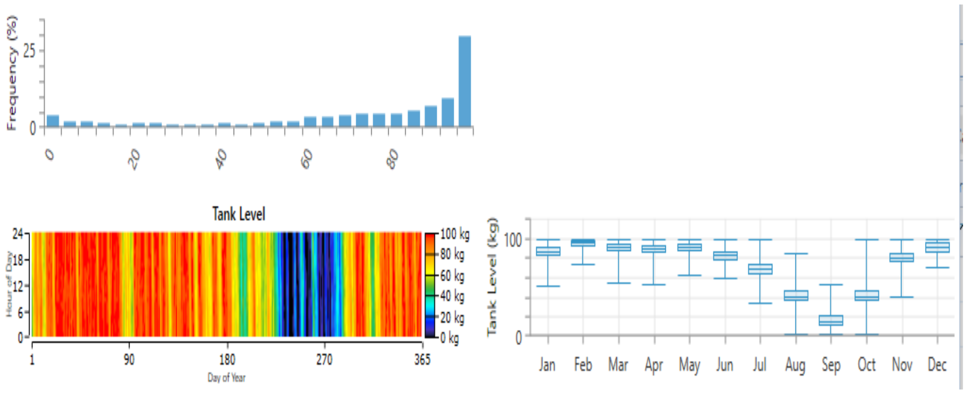


Figure 42. HTank Level (100 kg) (HOMER Pro)

HTank: In the beginning of the year, the hydrogen tank contained 50% of its capacity (50.0 kg). However, at the end of the year, it contained 100% (100.00 kg), as illustrated for the simulation in Figure 42. The energy storage capacity and specifications of the Hydrogen Tank (HTank) are presented in Table 9.

Table 9. HTank Specification and Storage Capacity

Properties	Value
Hydrogen Storage Capacity	100 kg
Energy Storage Capacity	3,333 kWh
Tank Autonomy	133 hr
Capital Expenses	80,000€
O&M expenses	3,878.25€

System Converter (95.0 kW): The generic 95 kW system converter loses 11,351 kWh/year of energy by the inverter and 62.8 kWh/year by the rectifier. The capacity factor of the inverter was 26.3%, and for the rectifier, 0.146%. The converter's property (Table 10) and power output are given in Figure 43.

Table 10 Converter's Power Properties of MESHS 1 (HOMER Pro)

Properties	Inverter Value	Rectifier Value
Capacity	93.5 kW	93.5 kW
Maximum Power Output	84.8 kW	29.3 kW
Maximum Energy In	227,030 kWh/year	1,256 kWh/year
Maximum Energy Output	215,678 kWh/year	1,194 kWh/year
Energy Losses	11, 351 kWh/year	62.8 kWh/year
Capacity Factor	26.3%	0.146%
Hours of Operation	86,76 hrs /year	84.0 hrs /year

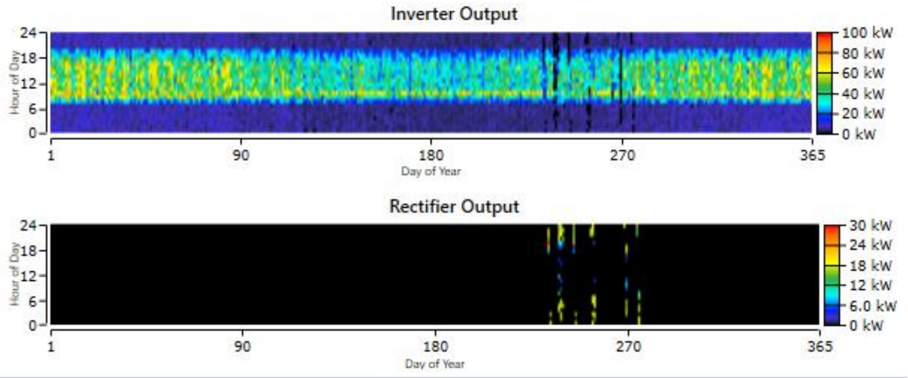


Figure 43. Converter power output (inverter and rectifier) MESHS 1

4.2.2 Feasibility Assessment of MESHS Model 1

a) Technical Feasibility MESHS Model 1

Energy Production and Consumption

The total energy generated from the MESHS Model 1, combining the individual system components' energy generation, including PV, WT, diesel genset, and fuel cell (H_2), is illustrated in Table 11.

Table 11. Total Energy Production by the Component OF MESHS 1 (HOMER Pro)

Component	Production (kWh/ year)	Rate (%)
PV (SunPower E20-327)	29, 461 kWh/ year	3.90 %
WT [XANT M-21 (100Kw)]	646,720 kWh/ year	85.6 %
100kW fixed capacity Genset [Gen100 (D)]	4,578 kWh/ year	0.606 %
Fuel Cell (H_2)	74,745 kWh/ year	9.89 %
Total	755,503 kWh/ year	100 %

The monthly total energy production by the energy components is presented in Figure 44.

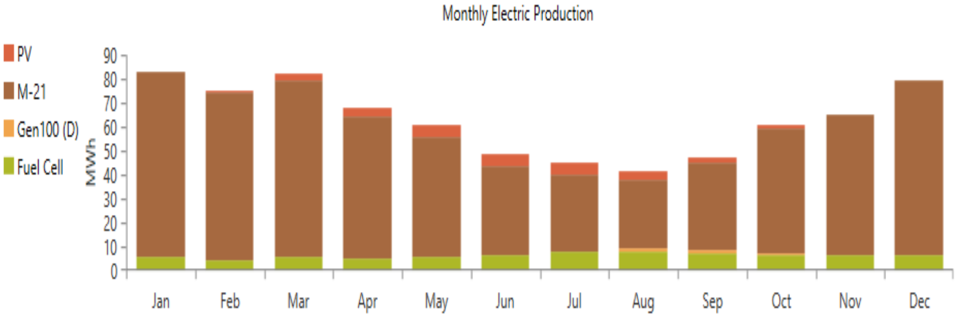


Figure 44. Monthly energy production by the components of MESHS Model 1 (HOMER Pro)

Total energy consumption by the MESHS model 1 was 496,013 kWh/year, which comprised energy consumption by the EV charging (AC Load), 219,000 kWh/year (44.22%), and electrolyzer consumption, 277,013 kWh/year (55.8%).

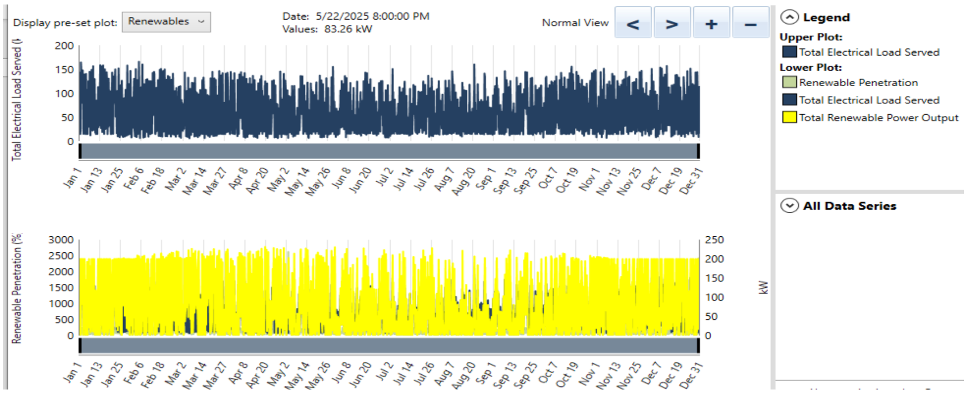


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Figure 45. Renewable power output by (HOMER Pro)

The maximum renewable penetration was 2,622% in Figure 45. The renewable fraction (RF) 97.3 % means maximum 97.3 per cent of energy delivered to the load generated from the renewable power sources.

Reliability or viability

The unmet electrical load and hydrogen load of 0 kWh/year indicated the energy model as 100% reliable (Figure 46).

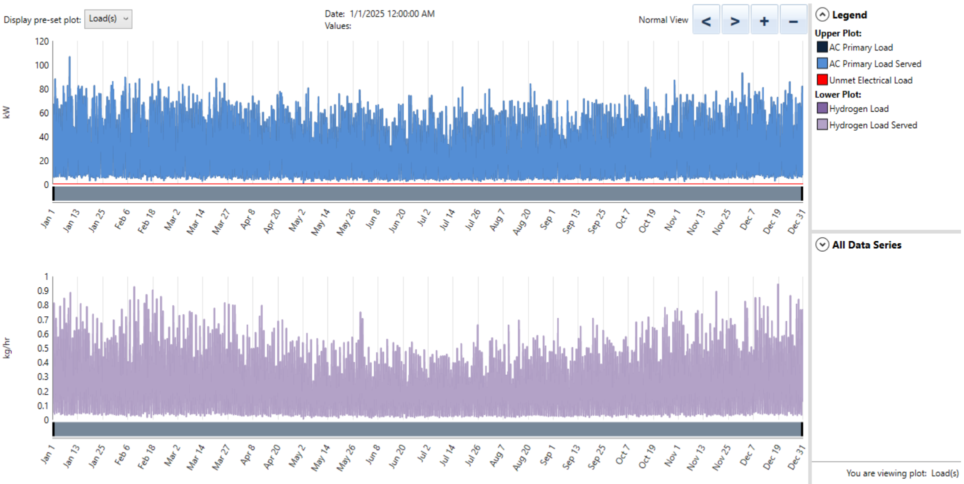

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Figure 46. Loads by the Proposed MESHS Model 1

b) Economic Feasibility Assessment MESHS Model 1

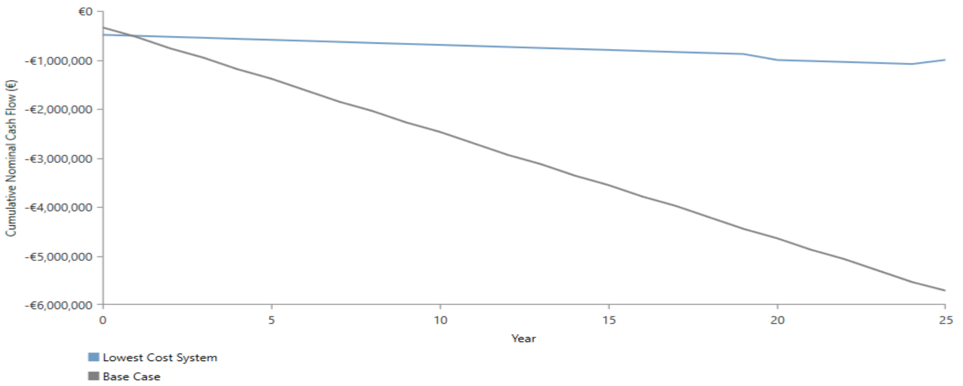
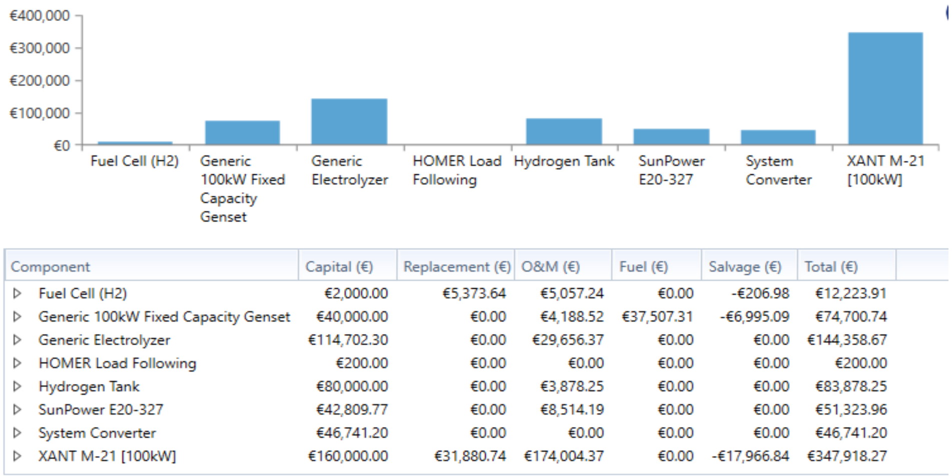


Figure 47. Cumulative discounted cash flows with H_2 storage (HOMER Pro)

The cumulative discounted cash flows diagram in Figure 47 demonstrates how the proposed hybrid energy storage model saves the economy more than the base system over the lifetime (25 years).



Component	Capital (€)	Replacement (€)	O&M (€)	Fuel (€)	Salvage (€)	Total (€)
▷ Fuel Cell (H2)	€2,000.00	€5,373.64	€5,057.24	€0.00	-€206.98	€12,223.91
▷ Generic 100kW Fixed Capacity Genset	€40,000.00	€0.00	€4,188.52	€37,507.31	-€6,995.09	€74,700.74
▷ Generic Electrolyzer	€114,702.30	€0.00	€29,656.37	€0.00	€0.00	€144,358.67
▷ HOMER Load Following	€200.00	€0.00	€0.00	€0.00	€0.00	€200.00
▷ Hydrogen Tank	€80,000.00	€0.00	€3,878.25	€0.00	€0.00	€83,878.25
▷ SunPower E20-327	€42,809.77	€0.00	€8,514.19	€0.00	€0.00	€51,323.96
▷ System Converter	€46,741.20	€0.00	€0.00	€0.00	€0.00	€46,741.20
▷ XANT M-21 [100kW]	€160,000.00	€31,880.74	€174,004.37	€0.00	-€17,966.84	€347,918.27

Figure 48. Net present cost of the proposed system components

Figure 48 presents the life cycle costs, or total net present costs, of all the system components. The largest share of NPC, €347,918.27, comes from the wind turbine [XANT M-21 (100 kW)]. On the contrary, the fuel cell (H_2) highlighted a low NPC (€12,223.78). The NPC of the generic electrolyzer is €144,358.67; the NPC of the genset (100 kW fixed capacity) is €74,700.74; the PV (SunPower E320-327) is €51,323.96; the system converter's NPC is €46,741.20; the hydrogen storage tank is €83,878.25; and the lowest NPC for the LF controller (HOMER load following) is €200.00.

Table 12. Economic Highlights for MESHS Model 1

Economic Metrics	Base System	Proposed System (MESHS Model 1)
Life Cycle Cost or Total (NPC)	€3.12M	€761, 345.00
Capital Expenses (CAPEX)	€322,630.91	€486, 453.00
O & M Expenses (OPEX)	€216,479	€21,264.00
Levelized Cost of Energy (LCOE)	€1.10	€0.269/kWh
Levelized Cost of Hydrogen LCOH	€ 136.00/kg	€12.9/kg
Return on Investment (ROI)	n/a	115 %
Internal Rate of Return (IRR)	n/a	114 %
Simple Payback Period	n/a	0.94 (less than a year)
Fuel Consumption (Diesel)	96,359 L/ year	1,612 L/ year

The life cycle cost (LCC), or total NPC, OPEX, LCOE, and LCOH, of the proposed hybrid model presents significantly lower prices in Table 12. The proposed hybrid model significantly outperforms the base system. Furthermore, diesel consumed by the proposed system is much less than that of the base model. However, the capital expenses (CAPEX) are higher for the proposed MESHS model 1 than the base model. The high capital expenses support the results highlighted by the survey findings. The simple payback period of 0.94 (less than a year), the high IRR of 114%, and the fastest ROI of 115% by the proposed system presented high profitability and economic feasibility of the proposed multi-energy storage hybrid system (MESHS Model 1) with H_2 storage.

Fuel Consumption

The proposed MESHS model 1 consumed 1,612 L of diesel per year, while the base model consumed about 96,359 L of diesel per year. So, the proposed system saves a significant amount of diesel (94,747 L/year), which also reduces the dependency on diesel fuel for EV charging in the study location. Figure 49 illustrates the hourly and annual fuel consumption profiles.

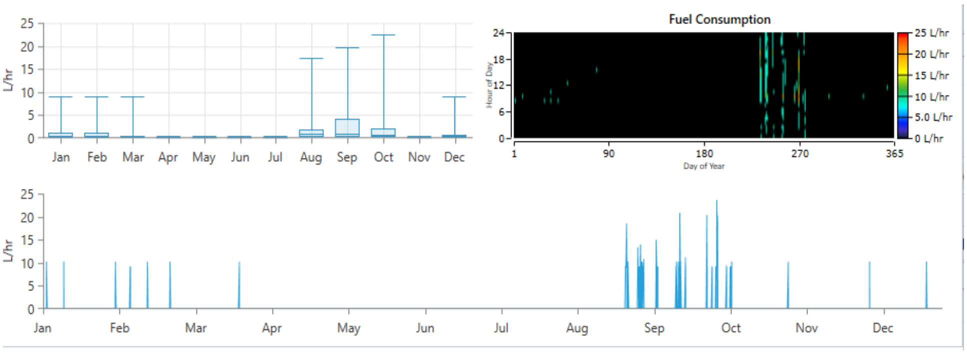


Figure 49. Fuel Consumption (Diesel) for MESHS Model 1 (HOMER Pro)

4.2.3 Environmental Emission Measurement of MESHS Model 1

The proposed system presented the yearly emission (GHGs) from electricity generation. The winning hybrid energy storage system (MESHS model 1) resulted in yearly CO_2 emissions of 4,216 kg, while the base system generated 250,107 kg of CO_2 emissions per year. Therefore, the proposed model reduced the amount of CO_2 emissions by 98.4% compared to the base model. Simultaneously, other greenhouse gases (GHG), including CO, NO, SO_2, other unburned hydrocarbons, and particulate matter released by the proposed MESHS model 1, were found to be 98.3% less than the baseline system. The GHG emissions measured (HOMER Pro), including the emission comparison, are presented in Table 13.

Table 13 Emission Comparison proposed MESHS 1 with base model (HOMER Pro)

Pollutant (GHG)	Emission by proposed (MESHS model 1)	Emission by Base Model	Emission Reduction by ↓ proposed system (%)
Carbon Dioxide (CO_2)	4,216 kg/ year	252,034 kg/ year	98.3%
Carbon Monoxide (CO)	28.7 kg/ year	1,715 kg/ year	98.3%
Nitrogen Oxides (NO)	2.29 kg/ year	137 kg/ year	98.3%
Sulfur Dioxide (SO_2)	10.3 kg/ year	618 kg/ year	98.3%
Unburned Hydrocarbons	1.16 kg/ year	69.4 kg/ year	98.3%
Particulate Matter	0.115 kg/ year	6.86 kg/ year	98.3%

Overall, the proposed multi-energy storage hybrid system (MESHS Model 1) with hydrogen storage, WT/PV/Gen100(D)/Electrolyzer/HTank/Fuel Cell/Converter (AC-DC)/Controller (LF), offers a cost-effective, technically viable, and eco-friendly hybrid energy storage solution for EV charging with life cycle cost (LCC) or total NPC (€761,345), LCOE (€0.269/kWh), LCOH (€12.9/kWh), OPEX (€21,264.00), RF (97.3%), and Unmet Load (0 kWh/year) with a slightly higher CAPEX (€486,453.00) and 98.3% less carbon emission (247,818.00 kg/year, CO_2 reduction) than the base system. Additionally, the excess electricity, 248,076 kWh/year, which is approximately 32.8%, could be utilized by the electrolyzer to produce hydrogen for external purposes or stored in the hydrogen storage tank (HTank), which could serve the fuel cell for re-electrification when required. The results highlighted the technical, economic, and environmental potential with the H_2-based MESHS model 1 for establishing EV charging infrastructure in the study region, Utsjoki, Finland.

4.2.4 Simulation Results for the MESHS Model 2 (with Lithium-ion battery)

a) System Overview

This multi-energy storage system (MESHS model 2) with a lithium-ion battery is designed for off-grid EV charging in Utsjoki, Finland. It includes wind, solar PV, a 100kW fixed capacity diesel generator, lithium-ion battery storage, a generic converter (AC-DC), and a controller (LF). The main configuration components of the MESHS model 2 are presented (Figure 50) as WT/PV/Diesel Genset/Lithium-ion Battery /Converter (AC-DC)/Controller (LF). The estimated EVCS load was considered 600 kWh/day, with a peak load of 92.99 kW and a load factor of 0.27. The project lifetime considered was 25.0 years.

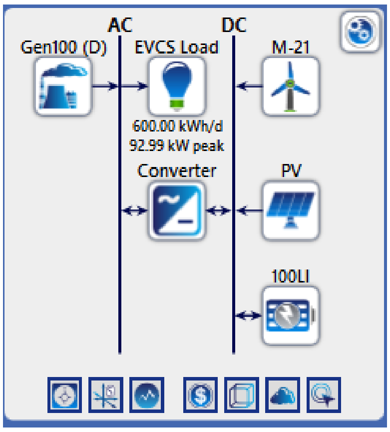
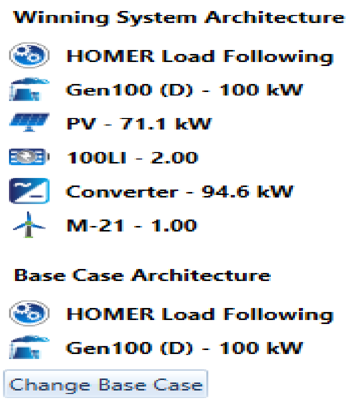


Figure 50. Schematic diagram of the optimized MESHS model 2 (with Lithium-ion storage)

b) Optimization Outcome



Winning System Architecture

HOMER Load Following
Gen100 (D) - 100 kW
PV - 71.1 kW
100LI - 2.00
Converter - 94.6 kW
M-21 - 1.00

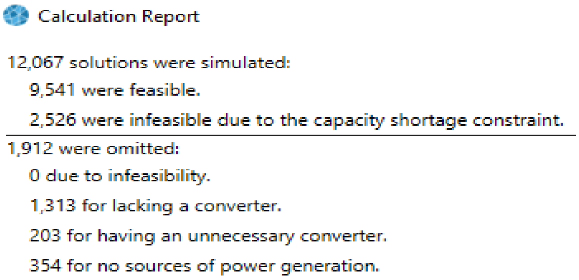
Base Case Architecture

HOMER Load Following
Gen100 (D) - 100 kW

Figure 51. System architecture for MESHS model 2 optimized (HOMER Pro)

From the optimization of the MESHS Model 2 with battery storage at 600kWh/day EVCS load and a diesel price € 1.80, the winning system and base case system resulted in the components illustrated in Figure 51.

The base system presents a 100kW diesel generator, and a controller (LF) while the winning system comprises a PV (71.1kW), WT (100kW), a generic fixed capacity 100kW diesel generator Gen100 (D), generic 100kW Lithium-ion battery (2.0), Converter (93.2kW), and controller (LF) (HOMER Pro).



Calculation Report

12,067 solutions were simulated:
- 9,541 were feasible.
- 2,526 were infeasible due to the capacity shortage constraint.

1,912 were omitted:
- 0 due to infeasibility.
- 1,313 for lacking a converter.
- 203 for having an unnecessary converter.
- 354 for no sources of power generation.

Figure 52. Simulation calculation report for MESHS model 2

The optimized model calculated 12,067 solutions during the simulation. The reported feasible solutions number was 9,541 and 2,526 were found to be infeasible due to the constraints of capacity shortage (Figure 52).

c) Optimized Component Properties

Wind Turbine (100 kW): The rated capacity of the (XANT M-21) wind turbine was 100 kW (one unit). The annual energy production was 323,360 kWh, which was 78.9% of the total generation of the system (€409,990). The capacity factor was 36.9%. Total hours of operation: 7,602 hrs./year. The wind penetration is 148%. The life cycle cost (NPC) was €347,918.27, and the levelized cost was €0.0416/kWh. The power output of the wind turbine is as illustrated in Figure 53.

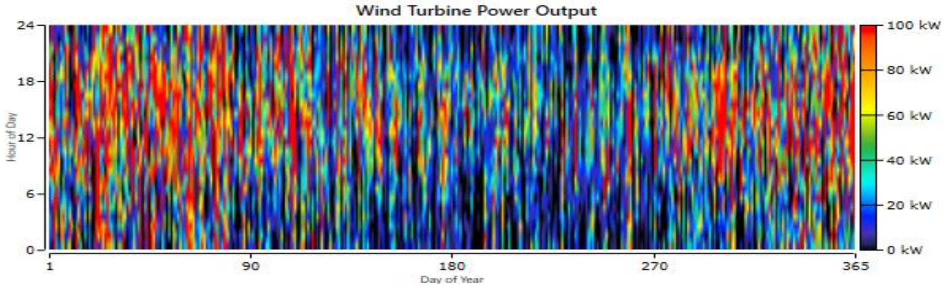


Figure 53. Wind power output of MESHS model 2

Solar PV (71.1 kW): The rated capacity of the selected solar photovoltaic panel (SunPower E20-327) was 71.1 kW at the average electrical load demand of the EV station, 600kWh/day. The mean output of this PV panel was 174 kWh/day. Total hours of operation by the PV system were 4,379 hours/year. The lower value of the capacity factors, 10.2% of the photovoltaic output, was presented in the Arctic winter darkness and short daylight situation. Total annual energy production by this PV panel was 63,646 kWh/year, which is only 15.5% of the total energy production by the proposed system. PV power output is as illustrated in Figure 54.

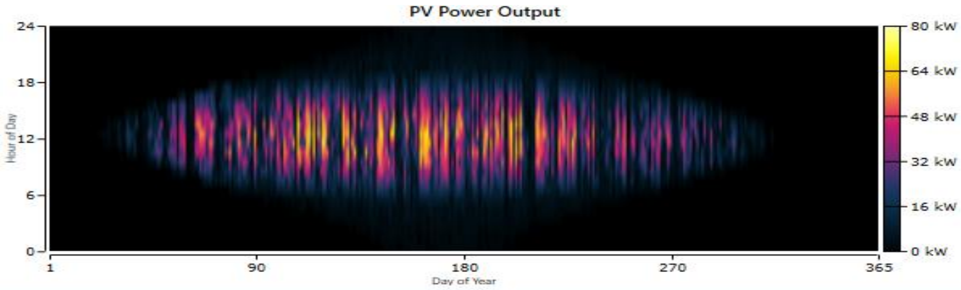


Figure 54. PV power output MESHS model 2

Diesel Generator [Gen100 (D)]: A generic 100kW (fixed capacity) generator, Gen100 (D), was used in the proposed MESHS model 2. The annual energy production capacity of this diesel genset was 22,912 kWh/year, which was around 5.59% of the total energy production by the proposed model. Fuel consumption for the genset is 7,936 L/year (backup for emergencies). Hours of operation were 764 hrs./year, capacity factor was 2.62%, and mean electrical efficiency was 29.3%. The specific fuel consumption is 0.346 L/kWh, and the marginal generation cost is €0.455 per kWh. The diesel generator's fuel output is illustrated in Figure 55.

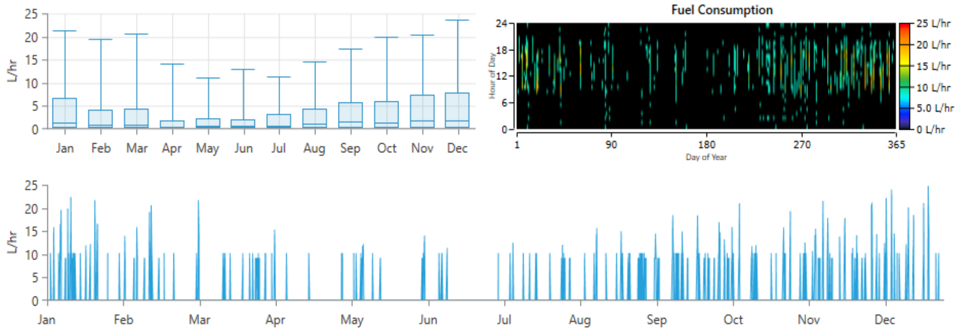


Figure 55. Diesel Genset Fuel Consumption and Power Output (MESHS Model 2)

System Converter (94.6 kW): The generic 94.6 kW system converter loses 10,412 kWh/year of energy by the inverter and 87.3 kWh/year by the rectifier. The capacity factor for the inverter was 23.9%, and for the rectifier, 0.200%. The converter, including the inverter and rectifier hourly and annual power output and properties, is illustrated in Figure 56 and Table 14.

Table 14. Converter's Power Output for MESHS 2

Properties	Inverter Value	Rectifier Value
Capacity	94.6 kW	94.6 kW
Maximum Power Output	85.9 kW	19.6 kW
Maximum Energy In	208,246 kWh/year	1,746 kWh/year
Maximum Energy Output	197,834 kWh/year	1,659 kWh/year
Energy Losses	10, 412 kWh/year	87.3 kWh/year
Capacity Factor	23.9%	0.200%

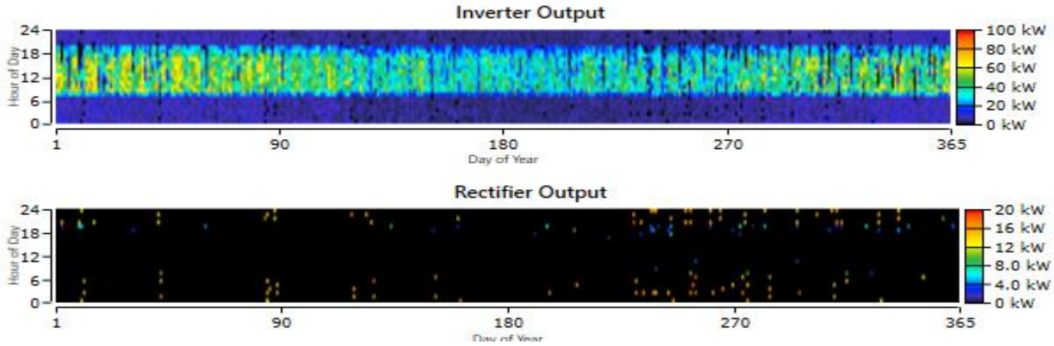


Figure 56. Converter power output (inverter and rectifier) MESHS Model 2

Battery Storage (Generic 100 kWh Lithium-ion): The nominal capacity of the lithium-ion battery was 200 kWh (for qty. 2), selected while optimizing the MESHS model 2. The lifetime throughput by the selected battery was 496,009 kWh over 15.00 years (per qty.). The battery state of charge (SOC) (percentage of the charge to the maximum charge ratio) and frequency are presented in Figure 57.

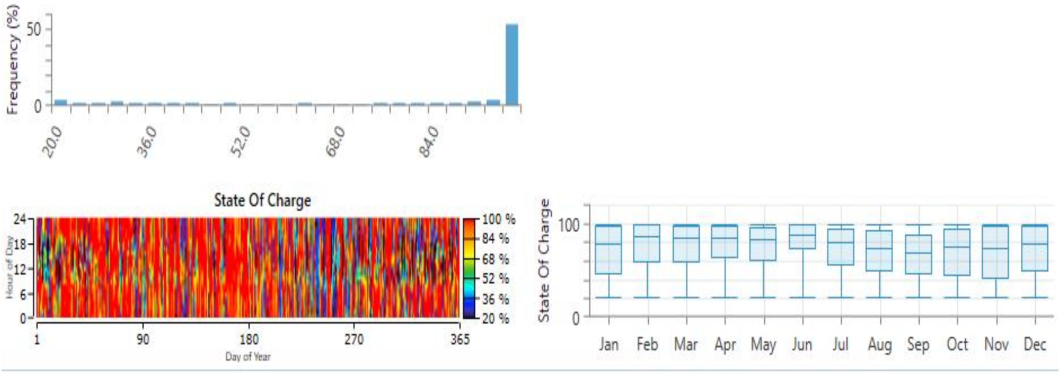


Figure 57. The state of charge (SOC) and frequency of 100kW generic lithium-ion battery (HOMER Pro)

Other properties of the battery storage employed in MESHS model 2 are outlined in Table 15.

Table 15. Lithium-ion battery properties

Battery Properties (100kW generic Li-ion)	Value
No. of Batteries	2
String Size	1.00 battery
String in Parallel	2.00 strings
Bus Voltage	600 V
Autonomy	6.40 hour
Nominal Capacity	200kWh
Lifetime Throughput	496,009kWh
Annual Throughput	33,067 kWh/year
Expected Battery Life (per qty.)	15.0 year

4.2.5 Feasibility Assessment of MESHS Model 2

a) Technical Feasibility

Energy Production and Consumption by MESHS Model 2

The total energy of 409,990 kWh/year produced by the energy components of MESHS model 2, which combines energy production from solar PV, WT, and a 100 kW diesel genset, is presented in Table 16. In addition, the monthly electrical production by the system component of the MESHS model 2 is illustrated in Figure 58.

Table 16. Total Energy Production by the Component

Component	Production (kWh/ year)	Rate (%)
PV (SunPower E20-327)	63, 642 kWh/ year	15.5 %
WT [XANT M-21 (100Kw)]	323,360 kWh/ year	78.9 %
100kW fixed capacity Genset [Gen100 (D)]	22,988 kWh/ year	5.61 %
Total	409,990 kWh/ year	100 %

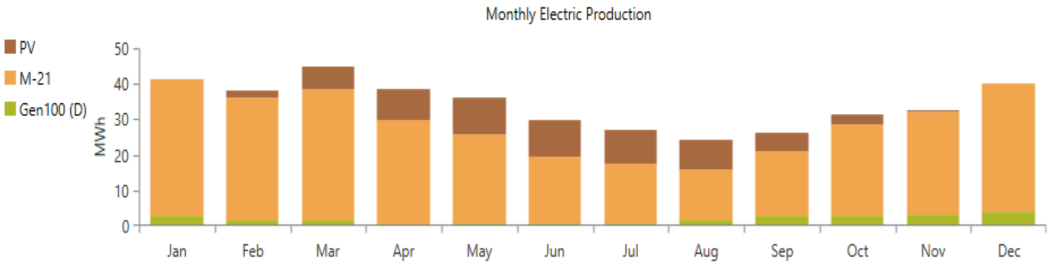


Figure 58. Monthly electric production by system components of MESHS model 2 (HOMER Pro)

Total energy consumption of 219,000 kWh/year in the MESHS model 2 was covered by the AC Load Primary Load for the EV charging (100.00%).

Renewables

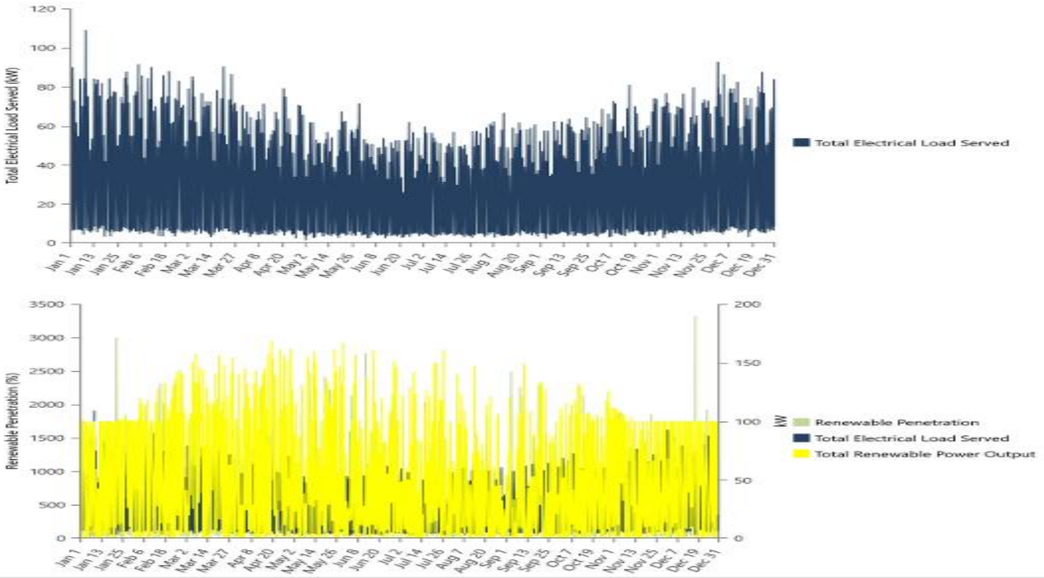


Figure 59. Renewable power output of the MESHS model 2 (HOMER Pro)

Figure 59 illustrates that renewable power sources generated a percentage of the energy delivered to the load by the MESHS model 2. The maximum renewable penetration was 3,319%, and the renewable fraction (RF) was 89.5%.

Reliability or viability

From the load output by HOMER, no unmet electrical load is observed (0 kWh/year), as illustrated in Fig. 2, and the model also resulted in no capacity shortage, which ensured the viability (100%) of the optimized energy model 2.

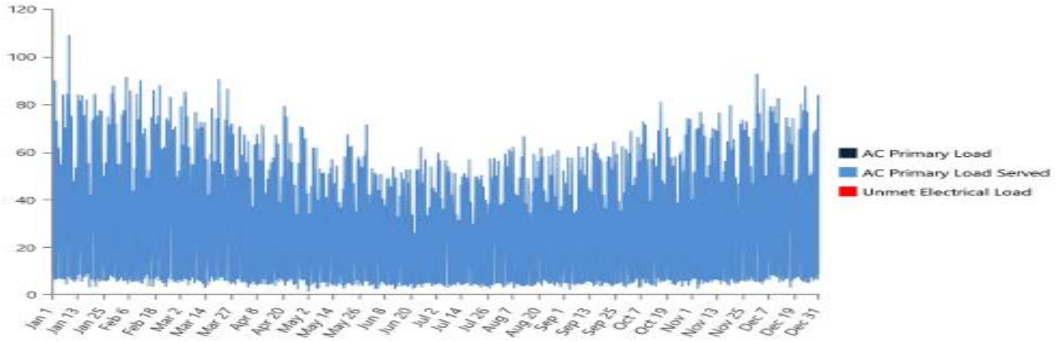
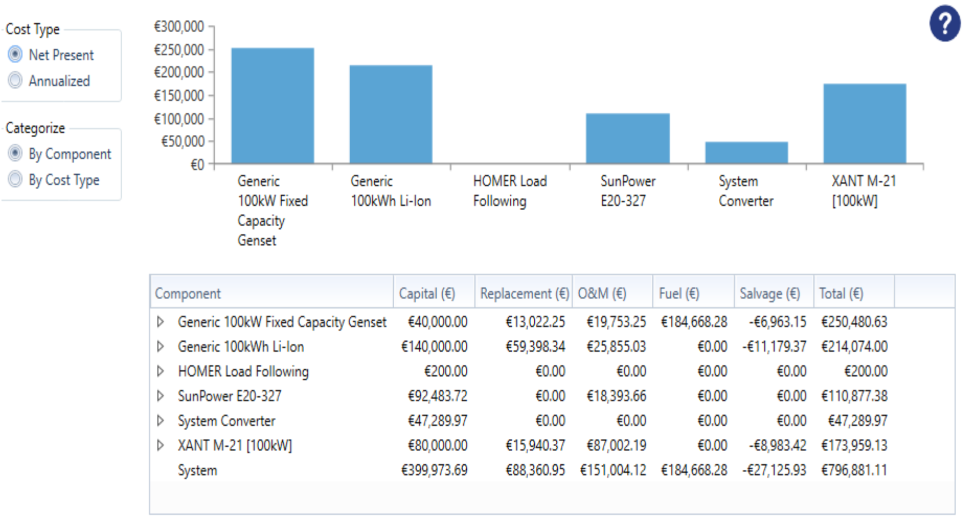


Figure 60. Electric Loads by the Proposed MESHS Model 2 (HOMER Pro)

b) Economic Feasibility Assessment

The life cycle costs, or total NPC, of the system components (MESHS model 2) are presented in Figure 61. The highest total life cycle costs, or NPC, of €250,480.63 resulted from the genset (100 kW fixed capacity), followed by the NPC of €214,074.00 of the generic lithium-ion batteries (100 kWh). The NPC of the wind turbine [XANT M-21 (100 kW)] observed €173,959.13. The PV (SunPower E320-327) had an NPC of €110,877.38, the system converter had an NPC of €47,289.97, and the LF controller (HOMER load following) had the lowest NPC of €200.00. The NPC of the overall system resulted from totaling the life cycle costs of all the system components, resulting in €796,881.


Cost Type
● Net Present
○ Annualized

Categorize
● By Component
○ By Cost Type

Component	Capital (€)	Replacement (€)	O&M (€)	Fuel (€)	Salvage (€)	Total (€)
▷ Generic 100kW Fixed Capacity Genset	€40,000.00	€13,022.25	€19,753.25	€184,668.28	-€6,963.15	€250,480.63
▷ Generic 100kWh Li-Ion	€140,000.00	€59,398.34	€25,855.03	€0.00	-€11,179.37	€214,074.00
▷ HOMER Load Following	€200.00	€0.00	€0.00	€0.00	€0.00	€200.00
▷ SunPower E20-327	€92,483.72	€0.00	€18,393.66	€0.00	€0.00	€110,877.38
▷ System Converter	€47,289.97	€0.00	€0.00	€0.00	€0.00	€47,289.97
▷ XANT M-21 [100kW]	€80,000.00	€15,940.37	€87,002.19	€0.00	-€8,983.42	€173,959.13
System	€399,973.69	€88,360.95	€151,004.12	€184,668.28	-€27,125.93	€796,881.11

Figure 61. Life cycle cost of the proposed system components of MESHS Model 2 (HOMER Pro)

The cumulative discounted cash flows diagram in Figure 62 highlighted the cost-effectiveness of the proposed hybrid energy storage model 2 compared with the base system over the project lifetime (25 years).

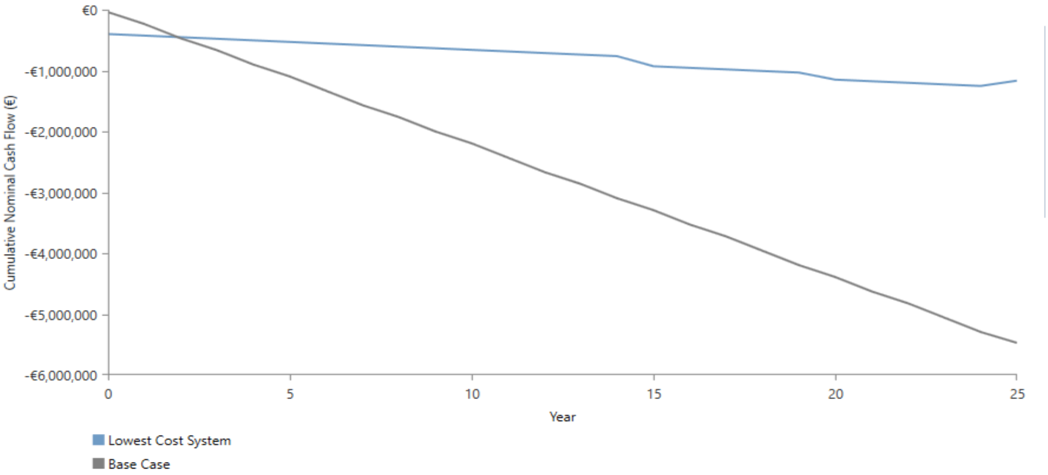


Figure 62. Cumulative discounted cash flows for MESHS model 2 (HOMER Pro)

Table 17 Economic Highlights of MESHS 2 (HOMER Pro)

Economic Metrics	Base System	Proposed System (MESHS Model 2)
LCC or Total NPC	€2.86M	€796,881
Capital Expenses (CAPEX)	€40,200	€399, 974
O & M Expenses (OPEX)	€217,757	€30,703
Levelized Cost of Energy (LCOE)	€1.01/kWh	€0.281/kWh
Levelized Cost of Storage LCOS	n/a	€0.259/ kWh
Return on Investment (ROI)	n/a	48%
Internal Rate of Return (IRR)	n/a	52 %
Simple Payback Period	n/a	1.91 (less than a year)
Fuel Consumption (Diesel)	98,937 L/ year	7,936 L/ year

From the economic insights in Table 17, the proposed hybrid model indicated significantly lower LCC or total NPC, OPEX, LCOE, and LCOS. The levelized cost of storage (LCOS) of the lithium-ion battery was estimated using the equation (U.S. DOE, 2014).

$$\mathrm{LCOS} = \frac{\text{Total life cycle costs of the lithium−ion battery}}{\text{Total discharged energy by the battery over the project life}} \qquad (14) \qquad =$$

$$\frac{€214{,}074}{(33{,}067\times 25)\mathrm{kWh}} = €.259/\mathrm{kWh}$$

In addition, the base system provided no storage; therefore, no LCOS resulted in the base model. Furthermore, diesel consumption by the proposed MESHS model 2 was noted to be less compared to the base model. However, the CAPEX for the proposed system was found to be higher than that of the base case. The proposed MESHS with lithium-ion battery storage demonstrated high financial feasibility and profitability, as indicated by a simple payback period of 1.91 years (less than two years), a high IRR of 52%, and the fastest ROI of 48%.

4.2.6 Environmental Emission Measurement of MESHS Model 2

The simulation highlighted yearly emission (GHGs), including CO_2, CO, NO, SO_2, other unburned hydrocarbons, and particulate matter released by the proposed MESHS model 2 from electricity generation. The yearly CO_2 emissions resulted in 20,757 kg/year by the MESHS model 2, while the base system generated 258,778 kg/year CO_2 emissions. Therefore, the proposed model reduced the amount of CO_2 emissions by 92% compared to the base model. Simultaneously, other greenhouse gases (GHGs) produced by the proposed MESHS model 2 were found to be 92% less than the baseline system. The emissions measured (HOMER Pro), including the emission comparison, are presented in Table 18.

Table. 18 Emission Comparison of MESHS Model 1 with Base Model (HOMER Pro)

Pollutants (GHGs)	Emission by Base Model	Emission by MESHS model 2	Emission Reduction by proposed system (%)
Carbon Dioxide (CO_2)	258,778 kg/ year	20,757 kg/ year	92%
Carbon Monoxide (CO)	1,760 kg/ year	141 kg/ year	92%
Nitrogen Oxides (NO)	141 kg/ year	11.3 kg/ year	92%
Sulfur Dioxide (SO_2)	634 kg/ year	50.9 kg/ year	92%
Unburned Hydrocarbons	71.2 kg/ year	5.71 kg/ year	92%
Particulate Matter	7.04 kg/ year	0.565 kg/ year	92%

In sum, the proposed lithium-ion battery-based MESHS Model 2 presented a cost-effective, technically viable, and environmentally friendly solution with the LCC (total NPC) (€796,881), LCOE (€0.281/kWh), LCOS (€0.259/kWh), OPEX (€30,703), RF (89.5%), and Unmet Load (0 kWh/year) with a slightly higher CAPEX (€399,974) and 92% less carbon emission (238,021 kg/year, CO_2 reduction) than the traditional diesel-based system.

4.3 Comparative Analysis of the Optimized MESHS Models

In this section, a comparison is presented between the two winning multi-energy storage hybrid system MESHS Model 1 with H_2 storage and Model 2 with Lithium-ion battery storage, (HOMER Pro). Following the evaluation criteria to support the objective of this research, a comparison between the two optimized hybrid energy storage models for EV charging is presented as follows,

Table 19. H_2 vs. Lithium-ion Battery Storage System for EV charging station

Evaluation Metrics	MESHS Model 1 (with H_2 Storage)	MESHS Model 2 (with Li-Ion Battery Storage)	Comparison
Configuration Components	WT/PV/ Diesel Genset/HTank/Fuel Cell (H_2)/Converter (AC-DC)/Controller (LF)	WT/PV/ Diesel Genset /Lithium-ion Battery /Converter (AC-DC)/Controller (LF)	MESHS Model 2 combines fewer components than Model 1
LCC or total NPC	€761, 345.00	€796,881	The total NPC of the MESHS model 1 is €35,536 less than Model 2
LCOE	€0.269/kWh	€0.281/kWh	LCOE of the MESHS Model 2 with lithium-ion battery is slightly higher by €0.012 per kWh of energy use.
Levelized Cost of Hydrogen/Storage (LCOH/LCOS)	€12.9/kg	€0.259/ kWh	H_2 storage presents higher levelized cost
CAPEX	€486, 453.00	€399, 974	Lithium-ion showing moderate expenditure with fewer components.
OPEX	€21,264.00	€30,703	The Lithium-ion based energy system highlighted high OPEX as it consumes more diesel.
RF	97.3%	89.5%	Lithium-ion battery storage-based MESHS model 2 utilizes renewables less effectively, which is crucial during long winter nights and low wind speed in the Arctic conditions.
Unmet Load	0 kWh/year	0 kWh/year	No insufficient energy generation by both the model which ensures reliability
Capacity Shortage	0 kWh/year	0 kWh/year	No capacity shortage observed by both the models, indicating system reliability by 100%
IRR	114%	52%	Hydrogen based hybrid storage model 1 presented higher economic return than lithium-ion battery-based model 2
ROI	115%	48%	MESHS model 1 presented better ROI
Payback Period (Simple)	0.94 years	1.91 years	Faster Payback by MESHS model 1
Excess Electricity	248,076 kWh/ year	176,933 kWh/ year	MESHS model 1 generates 28.7% higher electricity.
Autonomy Duration	133 hours	6.4 hours	MESHS model 1 storage autonomy is higher with hydrogen tank
Diesel Consumption	1,612 L/ year	7,936 L/ year	Diesel consumption is less with MESHS model 1
CO_2 Emission (kg/year)	4,216 kg/ year	20,757 kg/ year	MESHS model 1 produces less carbon emission per year than battery-based model 2

4.3.1 Performance Analysis: H_2 vs. Lithium-ion Battery Storage System

To ensure the viability of an energy system, the economic, technical and environmental assessment is presented from the comparison of the two hybrid systems with hydrogen storage (MESHS model 1) and with a Lithium-ion battery storage (MESHS model 2) for the EV charging solution in the Arctic region at Utsjoki, Finland.

Economic Performance

he LCC (total NPC) of the MESHS with a lithium-ion battery is higher (€796,881) than that of an H_2-storage-based system (€761,345.00). The LCOE of the H_2 storage-based model is comparatively lower (€.269/kWh) than that of the battery storage model (€.282/kWh). However, the levelized cost of hydrogen LCOH (energy capacity) is higher (€12.9/kWh) than the levelized cost of battery storage LCOS (€.259/kWh). Additionally, an H_2-storage-based model demands a higher CAPEX (€486,453.00) than battery storage (€399,974), which is a crucial factor while investing in such an EV charging business. Notwithstanding the high upfront costs and high levelized cost of hydrogen, the longer storage backup possible with a hydrogen storage system offers a promising energy storage solution highly required for adverse Arctic locations and reduces dependency on fossil fuels like diesel. A hydrogen-based model utilizes stored hydrogen via a fuel cell, so the operation cost is much less (€21,264.00) than that of battery storage (€30,703). Furthermore, a hydrogen-based hybrid storage model presented a higher internal return IRR (114%) than a lithium-ion battery (52%). Besides, the hydrogen storage system offered a better ROI (115%) compared to the battery storage system (48%). The MESHS model 2 with a lithium-ion battery, on the other hand, indicated a slightly slower payback time (1.91 years), while the H_2-based MESHS model 1 offers faster payback by 0.94 years, less than a year.

Technical Performance

MESHS Model 1 includes two storage components with an H_2 storage tank (HTank) and a fuel cell (H_2), while MESHS Model 2 comprises only storage with a lithium-ion battery. Both models utilize a higher percentage of RESs; however, the hydrogen-based model enhances system resilience necessary in Arctic weather conditions with nearly complete renewables integration, supporting system independence and promising environmental sustainability. Both models indicate high reliability (100%) with no insufficient energy generation (0 kWh/year unmet load observed) and no capacity shortage (0 kWh/year). The amount of excess electricity is higher in the hydrogen-based hybrid storage model (248,076 kWh/year) than the lithium-ion battery storage hybrid model (176,933 kWh/year); however, excess electricity can be utilized in model 1 by the electrolysis process to produce hydrogen that could be stored in the hydrogen tank or used for re-electrification by fuel cell (with stored H_2) or external hydrogen production, whereas the excess electricity in model 2 with lithium-ion battery storage is curtailed. Longer energy backup is required in Arctic conditions, considering the intermittency of renewable sources (such as solar and wind) for an off-grid charging station. It is possible to achieve a longer energy storage solution with H_2 storage (133 hours of autonomy) than short-term (6.4 hours of autonomy) storage with a lithium-ion battery.

Environmental Emission Analysis

From the simulation of HOMER Pro at a load of 600 kWh/day (AC) and a diesel price of €1.8, the battery storage MESHS model 2 consumes more diesel (7,936 L/year) and consequently produces more carbon emissions, including CO_2 (20,757 kg/year), CO (141 kg/year), NO (11.3 kg/year), SO_2 (50.9 kg/year), unburned hydrocarbons (5.71 kg/year), and particulate matter (0.565 kg/year). Whereas the H_2 storage-based MESHS model 1 consumes less diesel (1,612 L/year) and generates relatively fewer emissions: CO_2 (4,216 kg/year), CO (28.7 kg/year), NO (2.29 kg/year), SO_2 (10.3 kg/year), unburned hydrocarbons (1.16 kg/year), and particulate matter (0.115 kg/year). Analyzing the emissions, the H_2 storage-based MESHS model 1 resulted in 16,541 kg/year (79.68%) less CO_2 than the lithium-ion battery-based MESHS model 2. Therefore, considering the environmental emission reduction and achieving the EU decarbonization goal and sustainability, H_2 storage-based MESHS outperform the lithium-ion battery-based MESHS for EV charging in the selected Arctic location (Utsjoki, Finland).

In sum, the lithium-ion-based MESHS model 2 presented a more affordable capital investment (CAPEX) and a lower LCOS, whereas the H_2 storage-based MESHS model 1 offers a low LCC or total NPC, a low levelized cost of energy (LCOE), low operational expenses (OPEX), high reliability with higher renewable fractions (RF), no insufficient energy production or capacity shortages, and higher economic benefit with a higher internal rate of return and faster ROI and payback period (simple), which makes it the most viable long-term solution for off-grid EV charging infrastructure in Arctic regions like Utsjoki. Nevertheless, both systems outperformed the traditional diesel-based system while observing the HOMER Pro simulation tool with fewer renewable sources or without the integration of renewable energy sources.

4.4 Sensitivity Analysis

A sensitivity variable is a variable that is used as an input to determine several different values, as per HOMER Pro (n.d.-m). Every defined value is optimized using a different process by HOMER software. It employs a separate optimization procedure for each defined value. One of the reasons to perform a sensitivity analysis is that it is possible to determine the importance of the variable by defining a range of values. Furthermore, it is possible to understand how the solution changes following its inputs. Besides, sensitivity analysis helps find the intensity of transition on the findings by transitioning that variable (HOMER Energy, n.d.-m). Sensitivity Analysis, as described by Sayed et al. (2025), is an approach that supports evaluating the transition with necessary assumptions or variables that affect the financial outcomes of the model. He added that conducting a sensitivity analysis, parameters such as demand for EV charging, installation costs, and energy prices are varied to assess their impact on the project's financial feasibility (Sayed et al. 2025, p. 61858) HOMER Pro software, enables assessing the impact of variables such as global irradiance, fuel costs and load demand necessary for an energy system with a single simulation and analysis (HOMER Energy, n.d.-m).

Since fuel prices frequently changes, and one crucial objective of this research is to reduce the dependance on traditional fossil fuel like diesel, petrol, gasoline, or other natural gases for an off-grid EV charging infrastructure, a sensitivity analysis performed with various diesel prices for both the multi-energy storage hybrid system (MESHS model 1 and model 2) at 600kWh/day EV load.

4.4.1. Sensitivity Analysis for MESHS Model 1 (H_2 Storage)

Table 20. Economic variation with diesel fuel price changes (MESHS Model 1)

Sensitivity Variable (Diesel Price) (€/L)	LCC or Total (NPC) (€)	LCOE (€/kWh)	OPEX (€/year)	CAPEX (€)	IRR (%)	Simple Payback (year)	ROI (%)	LCOH (€/kWh)
1.7	758761.60	0.268	22526.78	467546.3	120	0.90	122	12.9
1.8	761345.00	0.269	21264.08	486453.3	114	0.94	115	12.9
2	765460.00	0.270	21427.1	488460.8	142	.75	145	13.0

The cost factors of the MESHS Model 1 for the 600kWh/day EV charging station at Utsjoki, Finland, were observed with the simulation results of HOMER at various diesel fuel prices (€1.7/€1.8/€2.0) presented in Table 20. Among the economic parameters, the LCC (total NPC), LCOE, OPEX, and CAPEX are found to increase when the various assumed diesel prices increase. The observation with other economic factors like IRR (114%), ROI (115%), and payback period (0.94 years) at the proposed diesel price of €1.8 has shown fluctuation with diesel prices of €1.7 and €2.0. At a low price of €1.7/L of diesel, the IRR (120%) and ROI (122%) were observed to be higher than when the diesel price was € 1.8/L, with a quick payback period of 0.90 years; however, at a diesel price of €2.0, the IRR (142%) and ROI (145%) were found to be higher, with a faster payback of 0.75 years. The levelized cost of hydrogen LCOH increased (€13.0 /kWh) when the diesel price increased to €2.0/L. However, below the price level of €2.0, the LCOH remained the same as €12.9 /L at diesel prices of €1.7/L and €1.8/L.

Table 21. Technical variation with diesel fuel price changes (MESHS Model 1)

Sensitivity Variable (Diesel Price) (€/L)	Ren Frac (RF) (%)	Capacity Shortage kWh/year	Unmet Load kWh/year	Excess Electricity (kWh/year)	Gen100 (D) Production (kWh)	Total Gen100 (D) Fuel (L)	Gen100 (D) O&M Cost (€/year)	Gen100 (D) Fuel Cost (€/year)
1.7	96.8	0	0	241,482	7073.22	2484	496	4222.67
1.8	97.9	0	0	248,076	4578.12	1612	324	2901.36
2	98.0	0	0	248,431	4378.72	1539	308	3078.03

With the diesel price at an increasing level (€1.7/€1.8/€2.0), the total diesel fuel consumption was significantly reduced by the MESHS with H_2 storage, thereby decreasing the operational cost of diesel and energy production with diesel. The renewable fraction (RF), on the other hand, has shown a slight but positive variation. Additionally, the amount of excess electricity increases (241,482 kWh/year, 248,076 kWh/year, and 248,431 kWh/year) at a slow rate, and no unmet load or capacity shortages are observed. Therefore, with various diesel prices, a multi-energy hybrid system with hydrogen storage is reliable at a 600 kWh/day load for the proposed EV charging station at Utsjoki, Finland. Thus, the MESHS model 1 has proven to be technically feasible when diesel fuel prices varied. The sensitive variations obtained from the HOMER Pro simulations are recorded in Table (21).

Table 22. Environmental impact on diesel price variation by MESHS Model 1

Sensitivity Variable (Diesel Fuel Price) (€/L)	Carbon Dioxide (CO_2) kg/ year	Carbon Monoxide (CO) kg/ year	Nitrogen Oxides (NO) kg/ year	Sulfur Dioxide (SO_2) kg/ year	Unburned Hydrocarbons kg/ year	Particulate Matter kg/ year
1.7	6,497	44.2	3.54	15.9	1.79	0.177
1.8	4,216	28.7	2.29	10.3	1.16	0.115
2	4,025	27.4	2.19	9.86	1.11	0.110

When the diesel price was lower (€1.7) for the estimated EV charging load 600kWh/day, HOMER Pro simulation showed a variation in emissions for MESHS model 1, as indicated in Table (22); specifically, the amount of carbon dioxide (CO_2) 6,497 kg/year and carbon monoxide (CO) 44.2 kg/year increased. There was a drop in the amount of carbon emissions when diesel prices gradually increased to €1.8 and €2.0. Other GHGs include sulfur dioxide (SO2) and nitrogen oxides (NO), unburned hydrocarbons, and unknown particulate objects, which showed little variation at different diesel prices; however, they decreased with the fuel cost decrement.

4.4.2 Sensitivity Analysis for MESHS Model 2 (Lithium-ion Battery)

Table 23. Economic variation with diesel fuel price changes by MESHS Model 2

Sensitivity Variable (Diesel Price) (€/L)	LCC or Total (NPC) (€)	LCOE (€/kWh)	LCOS) (€/kWh)	OPEX (€/year)	CAPEX (€)	IRR (%)	Simple Payback (year)	ROI (%)	Lithium-ion Battery Annual Throughput (kWh/ year)
1.7	786598.4	0.278	0.259	29908.65	399953.9	49	2.0	45	33070.38
1.8	796881.1	0.281	0.259	30702.52	399973.7	52	1.91	48	33067.28
2	817806.9	0.289	0.259	32335.27	399792.2	57	1.8	53	33068.65

From the Table (23), It is observed from the optimization of HOMER that with the variation in diesel fuel price (€1.7/€1.8/€2.0) at 600 kWh/day EVCS load, the economic factors of the energy system, like the LCC (total NPC), LCOE, OPEX, and CAPEX, have changed. Deviation is also observed with other economic factors like IRR, ROI, and payback period. The levelized cost of storage LCOS (€0.259/kWh) calculated using equation (14), however, observed no significant changes, since fuel prices had directly less effect on the annual energy throughput (33070.38 kWh/year, 33067.28 kWh/year, 33068.65 kWh/year) by the battery storage or the life cycle cost of the battery storage (€214074).

Table 24. Technical variation with diesel fuel price changes by MESHS Model 2

Sensitivity Variable (Diesel Price) (€/L)	Ren Frac (RF) (%)	Capacity Shortage kWh/ year	Unmet Load kWh/ year	Excess Electricity (kWh/ year)	Gen100 (D)/Production (kWh)	Gen100 (D)/ Total Fuel (Diesel) (L/ year)	Gen100 (D)/O&M Cost (€/year)
1.7	89.5	0	0	176,895	22913.95	7936.43	1528
1.8	89.5	0	0	176,933	22912.47	7936.06	1528
2	89.5	0	0	176,891	22966.09	7955.22	1532

The variables relevant to technical feasibility illustrated in Table 24, particularly RF, unmet load (0 kWh/year), and capacity shortage (0 kWh/year), that assess the reliability of hybrid energy systems, highlighted no significant changes with different diesel prices. However, slight variation has been observed in the excess electricity production (176,895 kWh/year, 176,933 kWh/year, and 176,891 kWh/year), which caused no significant impact on the reliability of the MESHS model 2 with battery storage. Due to price variation, slight changes have been noticed in the power production by the diesel genset and the O&M cost of the diesel.

Table 25. Environmental impact with diesel price variation by MESHS Model 2

Sensitivity Variable (Diesel Price) (€/L)	Carbon Dioxide (CO_2) kg/year	Carbon Monoxide (CO) kg/year	Nitrogen Oxides (NO) kg/year	Sulfur Dioxide (SO2) kg/year	Unburned Hydrocarbons kg/year	Particulate Matter kg/ year
1.7	20,758	141	11.3	50.9	5.71	0.565
1.8	20,757	142	11.3	50.9	5.71	0.565
2	20,808	142	11.3	51	5.73	0.566

There is little impact observed at the MESHS model 2 with the amount of carbon dioxide (CO_2) at various diesel prices, as indicated by the emission data presented in Table 25 from the HOMER Pro simulation. However, other GHG particles presented a very negligible impact on the diesel price changes.

5. Evaluation and Conclusion

Evaluation is one of the important steps considered for this study to present the results and findings. The evaluation model for this study involves findings from two different methods that include the survey outcomes and case study (simulation result analysis). By employing data triangulation through more than one process, an attempt has been made in this section to answer the research questions and complete the research objective.

Addressing the research question—How do the life cycle cost (LCC) and levelized cost of energy (LCOE) of renewable energy-based MESHS vary with fossil fuel (diesel)-based energy systems in Arctic conditions?

Analyzing the LCC/total (NPC) from the survey, 49% of stakeholders assumed the life cycle cost of the RES-based multi-energy-storage hybrid systems would be cost-effective and viable compared to the traditional fossil fuel (diesel)-based systems for an EV charging station in the Arctic region.

Assuming a 600 kWh/day (AC) EVCS load and a diesel price of €1.8, it is found from the simulation results (HOMER Pro) that the LCC (total NPC) of the proposed MESHS model 1 (with H_2 storage) is €761,345, whereas the life cycle cost of the base model (resulted by the simulation) is €3.12M. Thereby, the optimized model with H_2 storage saves total costs during the project life (25 years) by €2,358,655 (75.5%) compared to the base system with a highly diesel-based system.

Similarly, the LCC (total NPC) of the MESHS model 2 (with lithium-ion battery storage) is €796,881, whereas the LCC (total NPC) of the highly base system is €2.86M. Here, the optimized model with lithium-ion battery storage saves total costs during project life by €206,319 (72.1%) compared to the highly diesel-based system.

The simulation result about the LCC, or the total NPC, is proven to be lower than that of the highly diesel-based system with the hydrogen-based and lithium-ion battery-based hybrid energy storage models, which was supported by the majority of the stakeholders in the survey. Now, while comparing the two optimized hybrid energy storage models, MESHS Model 1 with hydrogen storage resulted in a lower life cycle cost (LCC) than MESHS Model 2 with lithium-ion storage.

About the levelized cost of energy (LCOE), when exploring the stakeholders' perspective, the majority, around 64% of the stakeholders (combining 26% who considered it lower, 3% who considered it significantly lower, and 35% who considered it comparable), indicated that the LCOE was lower for RES-based multi-energy-storage hybrid systems than the traditional diesel-based systems.

From the HOMER Pro simulation, when the EVCS load is 600 kWh/day and the diesel price is €1.8, the LCOE for the optimized hybrid energy model with hydrogen storage is €0.269/kWh, which is lower than the LCOE of the highly diesel-based base system, €1.10/kWh. Similarly, for the MESHS model 2, the LCOE is €0.281/kWh lower compared to the €1.01 LCOE of the highly diesel-based system. Thus, the findings supported the majority (64%) of the stakeholders' perspective regarding the LCOE. However, the MESHS Model 1 showed lower LCOE from the comparative analysis and the sensitivity analysis with various diesel prices between the H_2-based model and the lithium-ion battery-based storage hybrid system.

Now, answering the question, which multi-energy storage system (MESHS) results in the most cost-effective and viable model for grid-independent EV charging solutions in the Arctic region?

From the survey, wind (42%) resulted in the best renewable energy source, followed by hydropower (22%) and solar PV (17%). Among the storage technologies, hydrogen fuel cells (35%) and lithium-ion batteries (32%) were identified as the top storage technologies. Considering the availability of the resource data for optimization with HOMER Pro, hydropower was neglected from the two optimized hybrid energy storage models in this research. The two hybrid energy systems include H_2 storage for MESHS model 1 and lithium-ion battery storage for MESHS model 2. From the simulation result at 600 kWh/day EVCS load and €1.8 diesel price, both MESHS models demonstrated economical effectiveness and technical viability; however, with the comparative analysis between the two hybrid models and sensitivity analysis results with varying diesel prices, the multi-energy storage hybrid system with hydrogen storage (MESHS model 1) resulted in the most cost-effective and viable model for grid-independent EV charging solutions in the Arctic region with the lower LCC (total NPC) and lower LCOE, high IRR, faster payback period, and higher RF (97.3%) than the model using lithium-ion battery storage.

Referring to the question, how is the environmental impact of the renewable energy-based MESHS for EV charging stations compared with diesel-based systems under Arctic climate conditions?

From the HOMER simulation results, the yearly carbon emission and other GHG emissions measured and compared with the highly diesel-based energy system and with the emission measurement hydrogen-based storage model offer the most emission reduction, 98.3% (CO_2 4,216 kg/year), compared to the highly diesel-based system. Similarly, lithium-ion battery-based models reduce emissions by 92% with 20,757 kg/year of CO_2. However, the emission measured with the HOMER Pro software has some limitations, as it does not calculate the emission related to all the factors (raw materials extraction, component manufacture, transportation, recycling, etc.) throughout the entire life period. HOMER incorporated only the operational emissions.

The survey participants expressed concern about carbon emissions from traditional or diesel-based EV charging systems, and most of them significantly indicated that these multi-energy storage hybrid systems (MESHS) are important in reducing dependence on fossil fuels in Arctic regions. However, they also showed their concern about the impacts of renewable energy-based hybrid storage systems (MESHS), 56% associated with battery production or mining. Additionally, they identified the risks of hydrogen leakage as 55% normal, 9% moderate, 24% high, and 9% extreme concern, resulting in normal risks for hydrogen leakage in the Arctic. Another identified environmental impact was the land use for renewable infrastructure in the Arctic. Concern about noise from wind turbines in the Arctic was presented as 36% (30% of high concern and 6% as extreme concern). The factors associated with end-of-life disposal of storage systems in the Arctic were ranked as 47% (12% extreme, 35% high). Additionally, many of them advocated for the life cycle assessment by 73% (44% strongly, 29% agreed), which could present more accurate environmental impacts.

Addressing the question, how does the performance of different energy storage technologies vary with the extreme Arctic situation when integrated with RESs?

The 56% of stakeholders from the survey emphasized the importance of the role of energy storage technologies with RESs for the extreme Arctic situation. According to the survey data, liquid hydrogen (H_2) storage is considered the most effective energy storage technology, surpassing lithium-ion batteries. Comparing the two MESHS models with H_2 storage and with lithium-ion battery storage at 600kWh/day (AC) EVCS load and a €1.8 diesel price, both models utilize a higher percentage of RESs; however, the hydrogen-based model offers system resilience necessary in Arctic weather conditions with nearly complete renewables integration (RF 97.3%), supporting system independence more than the lithium-ion battery storage (RF 89.5%). Both hybrid storage models indicate high reliability (100%) with no unmet load (0 kWh/year) or no capacity shortage (0 kWh/year). However, lithium-ion battery autonomy is 6.4 hours, whereas the autonomy of the hydrogen storage tank is 133 hours. Therefore, hydrogen offers the most suitable storage performance for longer backup needs, considering the renewable intermittence in the dark winter night and low temperatures. However, to ensure the effectiveness of H_2 storage, better insulation is required for the storage tank (mentioned by 25% of survey participants), a cost-effective electrolyzer (24% mentioned), and cold-resistant fuel cells (22%). Consideration should also be taken for effective transportation (22%) and advanced safety protocols (6%).

Finally, addressing the research question, which policy measures and social factors may impact establishing MESHS-based EV charging solutions in the Arctic region?

The top policy measures identified from the survey are tax incentives (33%) and carbon pricing (28%). The other two measures were grants (22%) and cross-border collaboration (17%).

The key social factors that may impact establishing the charging solution in Arctic communities were the shortage of charging infrastructure (15 participants), the very high upfront investment for the new vehicles (7 participants), the lack of daylight in winter (5 participants), and anxiety about extreme cold weather (4 participants). Other identified barriers are cultural resistance to new technology (2 participants) and lack of awareness of benefits (1 participant). However, community involvement is considered the most important factor that impacts establishing MESHS-based EV charging solutions in the Arctic region.

In conclusion, with the techno-economic feasibility assessment, the renewable-based MESHS provide both financial and environmental benefits over the traditional diesel-based energy storage systems for grid-independent EV charging in the Arctic region. The LCC (total NPC) and LCOE are considerably lower in both the MESHS models, more specifically, MESHS model 1 with hydrogen storage. H_2 - based MESHS model demonstrated cost effectiveness and emerged as the most viable solution for EV charging, supported with lower LCC (total NPC), lower LCOE, higher RF, higher IRR, and longer autonomy. The Hydrogen-based MESHS model also offers the best environmental impact by reducing 98.3% CO_2 emissions compared to the diesel-based system. However, safety concerns come with the hydrogen (H_2) storage tank in the MESHS model 1. Lithium-ion-based MESHS model 2 also reduces the high amount of CO2 emissions by 92% to the diesel-based system, with environmental concerns about battery production and short autonomy (6.4 hours). With higher autonomy (133 hours), H_2-based MESHS offers better performance in Arctic weather conditions. Besides, policy measures such as tax incentives, carbon pricing, and social factors like community involvement significantly affect the successful deployment of MESHS for the EV charging station in the Arctic region.

6 Discussions and Future Recommendations

The potential factors that may differ the study outcomes and related aspects are mainly discussed in these sections, and future work scopes are also described.

This study involved a brief literature review. Extensive literature reviews, particularly on social and policy aspects, are required. Quantitative closed-end survey questionnaires were utilized to determine the opinion of industry experts, engineers, researchers, academics, policy makers, and local students or residents who have knowledge and interests in energy systems. However, a survey with open-ended questionnaires helps obtain more exclusive and detailed insights. In addition, qualitative interviews could bring more exclusive information about the energy industry's strategies and roadmaps regarding EV adoption and EV charging infrastructure development in the Arctic regions.

Optimization and feasibility studies with HOMER Pro software could be explored utilizing other sustainable sources like hydropower, geothermal energy, and biogas. Furthermore, other storage components such as thermal storage, flywheels, and lead-acid batteries were not tested. Software limitations also impacted the study. For instance, a survey participant suggested new batteries, such as sodium batteries, through an open feedback question (Q35). Due to the constraints of the HOMER Pro software, it was not possible to optimize. Optimizing other storage components could bring different outcomes than the storage technologies used in this study. A sensitivity analysis could be conducted, considering other parameters. Apart from various diesel prices, a sensitivity test was conducted employing various load demands and observing different outcomes. However, considering the length of this thesis study and period, those outcomes were not analyzed in this paper. As per the description of the HOMER Pro help documentation, hydrogen load should only be included when simulating a system that produces hydrogen for external applications (UL Renewables, n.d.). A hydrogen load was externally used without integrating it into the energy balance, as the LCOE observed increases significantly without adding an external hydrogen load in the H_2-storage-based MESHS model 1, which indicated that hydrogen storage systems could lead to higher costs unless the hydrogen produced is effectively utilized.

Furthermore, the renewable sources data, including solar GHI, air temperature, and wind data for the technical and economic feasibility assessment, are obtained from NASA's prediction of worldwide energy resources with the software HOMER Pro. The built-in HOMER resources provided solar and wind data for this multi-energy storage hybrid system analysis. However, the solar GHI data (ranges 22 years of average monthly GHI from July 1983 to June 2005), wind speed at 50 m above the earth's surface over 30 years (Jan 1984 to Dec 2013), and similarly, the monthly average air temperature over 30 years (Jan 1984 to Dec 2013). For this study, no current data were measured by the researcher, which may slightly differ from the data analysis outcomes with the originally measured recent data. Furthermore, the component price unit during simulation was set as € (Euro) considering the location of the case study, which was obtained from other sources with the units $ (USD). Therefore, the exact value of the economic parameters will differ.

Furthermore, this thesis study is limited to optimizing the grid-independent EV charging solution. Therefore, the cost comparison and emission measurements for grid-connected systems might bring different results in identifying the most cost-effective and environmentally friendly solutions.

To determine the ecological viability of an energy system, the overall greenhouse gas emissions (GHG) from the system are evaluated. The significant greenhouse gases contain CO_2, SO_2, NO, and other particles. Those GHG gases are detrimental to humans as well as animals and contribute to ecological damage (Bilal et al., 2024, p. 10). Electricity generation using only renewable sources results in nearly zero emissions. Electricity generation using fossil fuel (i.e., diesel) presents emissions. This study utilizing HOMER Pro measured the annual emissions produced during the operational period. The most well-known and widely applied technique for measuring the environmental effects of technical systems or services over the course of their whole lifespan is life cycle assessment.

It considers all stages of life, from the extraction of raw materials (cradle), manufacture, transportation, and usage until the end of life (grave) (Schelte, 2021, P.36). A comprehensive life cycle impact assessment may present more accurate emissions results.

Recommendation for Future Studies

More precise and recent renewable resources data (solar GHI, air temperature, and wind speed) can be measured and utilized for simulation, which will support bringing more accurate and reliable solutions with MESHS.

The multi-energy models could be simulated with other techniques, like transient energy models (TRNSYS), and the results could be compared. It is an alternative tool for simulating renewable energy systems and different modeled storage configurations. TRANSYS is especially well-suited for simulating photovoltaic systems, wind turbines, lithium-ion batteries, electrolyzers, H_2 storage tanks, diesel generators, compressors, fuel cells, and other controllers, as well as for conducting transient building load analysis. TRNSYS software, according to Haddad and Javani (2024), allows for the modeling of system behavior across time by offering the capability to analyze, simulate, and adjust the energy system's performance through a wide library of components. It provides all the components required for transient modeling and system simulation, allowing precise scaling and an in-depth examination of each component's transient behavior (Haddad and Javani, 2024, p. 6). Optimization techniques like particle swarm (PSO) or simulation with TRNSYS and MATLAB software could be employed with research similar to this thesis project.

A detailed reliability analysis for the EVCS charging allocation could also be conducted using techniques like Grey Wolf Optimization (GWO) (Sultan et al., 2022).

To find the best outcome on effectiveness, system resiliency, and emission reduction, as well as better utilization of excess electricity or solving the intermittency of the renewable resources, a grid-connected EV charging model or Vehicle to Grid (V2G) model can be simulated and compared with the grid-independent energy model.

To obtain detailed life cycle emission results, a life cycle environmental assessment, or LCA study, can be explored with other tools like OpenLCA and utilizing a database like the ecoinvent cutoff system. The extensive LCA will encompass a comprehensive life cycle analysis that includes raw material extraction, component manufacturing, transportation of system components, installation, electricity production, usage, and end-of-life management or recycling.

Finally, this thesis study is part of ongoing research for the project RESILIFY (W3.1), supported by the EU-Interreg program. The recommended tasks will be explored in future stages, which will bring a more exact solution for the EV charging infrastructure and help promote EV adoption within the Arctic region and other Nordic locations.

Clarification on AI Tools

The research student used tools like Quillbot AI, Duplichecker, and Grammarly mostly for paraphrasing, and grammatical corrections for writing. However, ChatGPT OpenAI was used while brainstorming and understanding formulas. The research student is fully aware of the subject and content used for the writing and follows the ethical standards of the University of Vaasa. However, the use of these tools did not change the student’s individual research contributions.

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Appendices

Appendix 1. Survey Questionnaires

General Information

1.What is your Background? (Choose one/more).

- ○ Electrical/Mechanical/Civil/ Environmental/Energy/Industrial/IT Engineer
- ○ Investor/ Business /Management/ Industry Personnel
- ○ Researcher/Academician/Energy Enthusiast
- ○ Policy Maker/Regulatory Authority
- ○ Local Inhabitant and General Student

2.What is your highest level of education? Single choice.

- ○ PhD
- ○ Master
- ○ Bachelor
- ○ High School/Vocational

3. How much aware are you aware of the Arctic weather conditions? Rating (1 = Least, 2 = Moderate, 3 = Normal, 4 = High, 5 = Advanced)

a.1 b. 2 c. 3 d. 4 e. 5

4.What is your level of awareness regarding renewable energy sources (RES) like solar, wind, and biomass? Rating (1 = Least, 2 = Moderate, 3 = Normal, 4 = High, 5 = Extreme)

a.1 b. 2 c. 3 d. 4 e. 5

5.How do you rank your understanding of energy storage systems?

a. High
b. Medium
c. Low
d. Poor

6.What is knowledge level with electric vehicle (EV) charging infrastructure? Rating 1 = Least, 2 = Moderate, 3 = Normal, 4 = High, 5 = Advanced)

a.1 b. 2 c. 3 d. 4 e. 5

Cost Factor Assessment

7.What would be the required initial investment for renewable energy-based EV charging infrastructure compared to diesel-based systems? Single choice.

- ○ High
- ○ Low
- ○ Moderate
- ○ Extreme
- ○ Very low

8. What do you think about the levelized costs of storage for renewable energy-based systems compared to the traditional fossil-fuel (diesel) based systems? Single choice.

- ○ Higher
- ○ Lower
- ○ Varies
- ○ Equal

9. What do you consider about the life cycle cost (NPC) of renewable energy-based MESHS versus diesel-based systems for EV charging stations? Single choice.

- Cost-effective and viable
- Very costly and non-viable
- Varies

10. How do you perceive the operational & maintenance cost-effectiveness (OPEX) of renewable energy-based EV charging solutions compared to diesel-based systems? Single choice.

- More Cost-Effective
- Cost-Effective
- Comparable
- Less Cost-Effective

11.What factors do you consider most important when evaluating the feasibility of EV charging solutions in remote Arctic areas? Multiple choice.

- Initial Capital Costs
- Energy Storage Efficiency
- Grid Independence
- Government Incentives
- Maintenance Costs
- Renewable Energy Sources Availability

12.How do you compare the levelized cost of energy (LCOE) of renewable-based multi-energy storage hybrid systems (MESHS) with diesel-based systems for Arctic EV charging? Single choice.

- Significantly Lower
- Lower
- Comparable
- Higher
- Significantly Higher

13.What are the biggest financial barriers to deploying MESHS in remote Arctic communities? Multiple choice.

- Funding/Investment
- High Upfront Costs
- ROI (Unpredictable)
- Maintenance Complexity
- Lack of Skilled Personnel

Technical Feasibility in Arctic Conditions

14. How important is it to integrate renewable energy sources into EV charging solutions in Arctic regions? Single choice.

- Somewhat important
- Neutral
- Somewhat not important
- Very important
- Not so important

15. Which renewable energy sources are mostly suitable for Arctic multi-energy storage systems (MESHS)? Multiple choice.

- Solar PV
- Wind
- Hydropower
- Biomass
- Geothermal

16. How important do you think the role of energy storage systems (e.g., batteries, thermal storage, hydrogen storage) is in the success of EV charging infrastructure? Single choice.

- Extremely important
- Somewhat important
- Neutral

- ○ Extremely not important

17. Which energy storage technology do you believe is most reliable for Arctic EV charging? Single choice.
    - ○ Lithium-ion Batteries
    - ○ Thermal Storage
    - ○ Hydrogen Fuel Cells
    - ○ Flywheel Storage
    - ○ Other________________

18. Which technical improvements are necessary to optimize hydrogen storage for Arctic conditions? Multiple choice.
    - ▪ Cold-Resistant Fuel Cells
    - ▪ Better Insulation for Tanks
    - ▪ Cheaper Electrolyzers
    - ▪ Effective Transportation
    - ▪ Advanced Safety Protocols

Environmental Impact Assessment

19.How concerned are you about carbon emissions from traditional or diesel-based EV charging systems? (1 = Least, 2 = Moderate, 3 = Normal, 4 = High, 5 = Extreme)

a.1 b. 2 c. 3 d. 4 e. 5

20.Rate the environmental impact associated with battery production/mining impacts in the Arctic. (1 = Least, 2 = Moderate, 3 = Normal, 4 = High, 5 = Extreme)

a.1 b. 2 c. 3 d. 4 e. 5

21.Rate the environmental concerns associated with hydrogen leakage risks in the Arctic. (1 = Least, 2 = Moderate, 3 = Normal, 4 = High, 5 = Extreme)

a.1 b. 2 c. 3 d. 4 e. 5

22.Rate the environmental concerns associated with land use for renewable Infrastructure in the Arctic. (1 = Least, 2 = Moderate, 3 = Normal, 4 = High, 5 = Extreme)

a.1 b. 2 c. 3 d. 4 e. 5

23.Rate the environmental factors related to noise from wind turbines in the Arctic. (1 = Least, 2 = Moderate, 3 = Normal, 4 = High, 5 = Extreme)

a.1 b. 2 c. 3 d. 4 e. 5

24.Rate the environmental factors associated with end-of-life disposal of storage systems in the Arctic. (1 = Least, 2 = Moderate, 3 = Normal, 4 = High, 5 = Extreme)

a.1 b. 2 c. 3 d. 4 e. 5

25.How important are these multi-energy storage hybrid systems (MESHS) in reducing dependence on fossil fuels in Arctic regions? Single choice.
- ○ Extremely important
- ○ Somewhat important
- ○ Neutral
- ○ Somewhat not important
- ○ Extremely not important

26. Do you think MESHS-based EV charging solutions can significantly reduce carbon emissions in Arctic conditions? Single choice.
    - ○ Somewhat Yes
    - ○ Yes
    - ○ Maybe
    - ○ No

27. Do you agree that lifecycle assessments (LCA) could measure and help reducing the environmental factors in this EV-charging project with multi-energy storage systems? Single choice.
    - ○ Strongly agree

- Agree
- Neutral
- Disagree

Social/Community Related Factors

28. How important is community involvement in designing multi-energy storage hybrid systems (MESHS) for Arctic EV charging? Single choice.
    - Extremely important
    - Somewhat important
    - Neutral
    - Not important

29. Which social barriers hinder establishing renewable based off-grid vehicle charging stations (with MESHS) in Arctic communities? (Select more than one)
    - Shortage of daylight during winter
    - Very high upfront vehicle costs
    - Limited charging infrastructure
    - Anxiety in extreme cold weather
    - Cultural resistance to new technology
    - Lack of awareness of benefits

30. How much can you depend on the hybrid renewable energy systems to continuously power EV charging in Arctic winters? Single choice.
    - Completely depend.
    - Somewhat depend.
    - Neutral
    - Cannot depend.

Policy Measure

31. How would you rate current government support for renewable energy projects in the Arctic region? Single choice.
    - Excellent
    - Good
    - Average
    - Poor
    - Very poor

32. Which policy measures would enhance multi-energy storage hybrid systems (MESHS) deployment? (Select more than one)
    - Carbon Pricing
    - Tax Incentives
    - Grants for Energy Pilot Projects
    - Cross-Border Collaboration

33. How critical is energy independence (e.g., reducing the imports and use of diesel) for Arctic communities? Single choice.
    - Extremely Critical
    - Critical
    - Neutral
    - Non-Critical

34. Which factors may negatively affect the broader uptake of EV adoption in the Arctic region? (Select more than one)
    - Limited driving range
    - Insufficient charging infrastructure
    - Consumer Concerns about storage life and availability
    - High upfront costs

35. Any Feedback or Comments

Appendix 2. Figures

Figure 63. QR code for the survey link