POLITECNICO DI TORINO

Master of Science

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Development of Phase 4 (100% Self-Sufficient) of the ZEESA Project – Zero Emission Energy Systems for the Arctic in Svalbard.

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Abstract

This study aims to conduct an initial analysis of Phase 4 of the ZEESA project (Zero Emission Energy System for the Arctic), which seeks to develop a completely self-sufficient energy system powered 100% by renewable sources. The project, launched in 2021 and located in the Svalbard archipelago, has as its main objective the reduction of fossil fuel use, particularly diesel, through the adoption of an innovative hybrid system.

The project is currently in Phase 3, which involves the installation of wind turbines. This thesis focuses on the planning and analysis of Phase 4, which aims to eliminate diesel entirely by adopting hydrogen as a long-term energy storage vector. The goal is to evaluate the technological strategies required to achieve full energy sustainability and address the main technical and economic challenges associated with the transition.

The study includes a theoretical assessment of possible technologies for hydrogen production, storage, and utilization, with particular attention to the selection of electrolyzers, fuel cells, and storage systems. An initial sizing of a hydrogen storage system without compressors will be estimated in order to ensure energy self-sufficiency while minimizing plant complexity. Furthermore, the spatial and economic feasibility of the proposed solution will be assessed, and its effectiveness will be verified through the analysis of historical energy production and consumption data. The entire study will be supported by simulation and modeling tools, particularly Microsoft Excel and Python.

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1. Introduction

1.1 General Overview

This thesis focuses on Phase 4 of the ZEESA project (Zero Emission Energy Systems for the Arctic), offering an in-depth analysis of the technologies required to complete the transition toward a fully renewable and zero-emission energy system. The introduction outlines:

- The objectives of the ZEESA project, its context, and the reasons for its initiation.
- Phase 4, with particular emphasis on the integration of hydrogen as an energy storage solution.
- The specific goals of the proposed thesis.

1.2 ZEESA Project

The ZEESA Project (Zero Emission Energy Systems for the Arctic) focuses on the design and implementation of integrated renewable thermal-electric energy systems specifically tailored for Arctic environments and highly demanding regions such as the Svalbard Islands. Aiming to facilitate the transition from fossil fuels to sustainable, zero-emission energy sources, ZEESA seeks to promote green growth and value creation for Norwegian enterprises [1][2].

Spanning the period from 2023 to 2026, the project explores innovative solutions that integrate photovoltaic energy production, advanced energy storage systems, and heat recovery technologies. Special attention is given to the social acceptance of these solutions within local communities, taking into account the unique context of Arctic climatic conditions and the crucial role of energy in ensuring the sustainability of remote settlements [3][8]. Experimental activities involving solar systems and dynamic modeling contribute to building a knowledge base for energy-efficient, reliable, and economically viable systems.

Overall Objectives of the Project:

- To develop a comprehensive knowledge base to enable a rapid, sustainable, and economically feasible transition of current Arctic energy systems toward 100% renewable energy supply.
- To design integrated thermal-electric systems that are reliable, energy- and cost-efficient, and capable of withstanding the extreme conditions of Arctic regions.
- To investigate the renewable energy resources available in the Arctic (such as solar and wind energy) and adapt technologies to maximize their production potential.
- To integrate innovative technologies, including energy storage, electrochemical conversion, and heat recovery, in order to optimize local use of generated energy.
- To examine social and cultural factors that may enhance the acceptance and implementation of zero-emission energy systems in Arctic communities.

Project Phases:

- **Phase 1 (2021):** Introduction of energy storage technologies and reduction of diesel consumption. Outcomes: 40% reduction in diesel usage through:
    - Installation of thermal storage systems to improve heat retention.

- Implementation of battery systems to enhance energy management and reduce reliance on diesel generators.
- Deployment of a pilot photovoltaic system to assess performance under Arctic conditions.
- Development of a hybrid control strategy to optimize the interaction between diesel generators, batteries, and renewable energy sources.

- **Phase 2 (2023):** Expansion of photovoltaic systems. Outcomes: Diesel consumption reduced by up to 70%.
  - Installation of photovoltaic systems with a total capacity of 300 kWp, consisting of 200 kWp ground-mounted and 100 kWp rooftop-mounted arrays.
  - Estimated annual energy production: approximately 220,000 kWh.

- **Phase 3 (~2025):**
  - Integration of wind energy to achieve a projected 90% reduction in diesel use.
  - Introduction of wind power systems to complement solar generation and address seasonal challenges (e.g., polar nights and extreme weather variability), ensuring more stable year-round energy supply.

- **Phase 4 (~2026):** Transition to 100% renewable energy through long-term hydrogen storage and fuel cell technologies.
  - Introduction of hydrogen as a long-term energy storage solution, produced locally via electrolysis powered by renewable energy [1][11].
  - Utilization of fuel cells to generate both electricity and heat sustainably during periods of low solar and wind output.

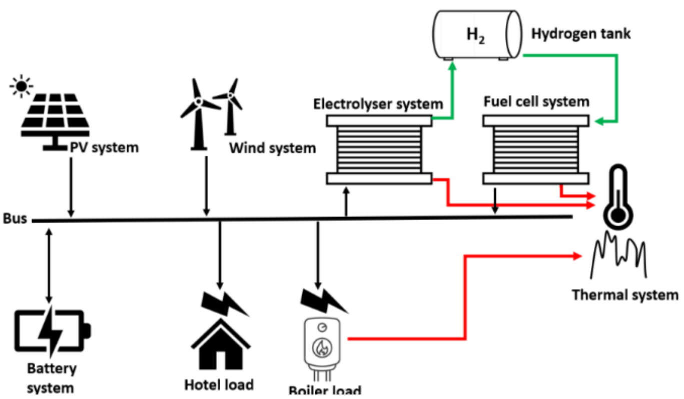

Figure 1: Scheme phase_4_ZEESA

Project Significance

The relationship between social development and energy availability is particularly evident in Arctic regions with limited access to energy. In such areas, the absence of traditional electrical grid infrastructure necessitates the development of innovative, localized energy solutions [8]. Local populations rely heavily on dependable energy sources for heating, essential services, and economic activities, making the establishment of sustainable energy infrastructure a critical priority [4][6].

Key Indicators for Energy Development

Energy progress can be assessed through two primary indicators:

- **Lambert Energy Index (LEI):** Evaluates the quality, quantity, and distribution of energy within a given context [5].

- **Human Development Index (HDI):** Measures national levels of longevity, education, and income [10].

Global studies have demonstrated a near-linear correlation between increases in the LEI and improvements in the HDI, up to a threshold of approximately LEI ≈ 0.45. Beyond this point, further advancements in energy provision do not significantly enhance living conditions, as energy systems tend to reach a state of stability and efficiency [5].

However, in the case of Svalbard, achieving this equilibrium is hindered by the region's unique geographic isolation and extreme climate [1].

Figure 3: Description of the figure

Energy Challenges in Svalbard

The main challenges associated with energy management in remote Arctic territories include:

- **Limited Access to Traditional Electrical Grids:** Low population density and geographic remoteness make the extension of conventional energy infrastructure economically unviable [6].

Figure 4: Description of the figure

- **Dependence on Diesel Generators:** Much of Svalbard's energy is currently produced through fossil fuel-based generators, which are costly, environmentally harmful, and incompatible with long-term decarbonization goals set for 2050 [4].

- **Technical Expertise and Maintenance:** Local energy systems are often constrained by a shortage of skilled personnel, increasing the risk of system failures and raising operational costs [7].

A Practical Example

International experiences have illustrated the potential of hybrid energy solutions. For instance, a study conducted in a remote Himalayan village demonstrated that a hybrid wind-hydro system, supplemented by battery storage and a diesel backup generator, achieved an 87% reduction in CO_2 emissions compared to a diesel-only system, with a resulting energy cost of $0.63 per kWh [9].

Such findings indicate that implementing similar hybrid systems in Svalbard could yield substantial economic and environmental benefits, contributing to Norway's national climate targets for 2030 and 2050 [6].

A ZEESA-Based Solution for Svalbard

The Norwegian government has emphasized the need for a more sustainable national economy to meet its climate commitments. The country's energy transition strategy aims to replace fossil fuels with renewable and emission-free sources while fostering national value creation and supporting green job growth [6].

In the Arctic, and specifically in Svalbard, energy consumption is still largely based on fossil fuels and costly imported solutions. The government has outlined a strategic goal to initiate the transition to a renewable energy system (RES) that aligns with local needs, opportunities, and environmental objectives [6].

A long-term target involves the decommissioning of the coal-fired power plant in Longyearbyen. This transition presents an opportunity to implement an environmentally sound, sustainable, reliable, and cost-effective energy system. However, the severe climatic conditions of Svalbard and the broader Arctic region require energy systems that are resilient to extreme weather and capable of operating with minimal on-site supervision due to logistical constraints [1].

Moreover, these systems must be compatible with the region's strong environmental and cultural protections and gain acceptance from local residents and businesses—factors that are essential for successful implementation and long-term sustainability [8].

1.3 The Strategic Role of Hydrogen in the Energy Transition

Hydrogen is increasingly recognized as one of the most promising solutions for the global energy transition, particularly in the context of achieving climate neutrality targets by 2050 [4]. Its versatility and broad applicability across multiple sectors make it a strategic vector for decarbonization.

- **Integration with Existing Infrastructure:**

Hydrogen can be blended with natural gas in existing distribution networks at concentrations of up to 15–20% without significantly affecting gas quality. This capability enables the gradual decarbonization of the gas grid while leveraging current infrastructure, thereby reducing the need for costly retrofits or replacements [4].

- **Transport Applications:**

Hydrogen is especially well-suited for heavy-duty transport, including trucks, trains, buses, ships, and even passenger vehicles. Compared to battery-powered alternatives, hydrogen-based systems typically require less installation space and offer faster refueling times. For example, hydrogen refueling stations occupy only about one-tenth of the space required by equivalent electric vehicle fast-charging facilities [4].

- **Zero-Emission Renewable Energy Production:**

Through the use of electrolyzers, electricity generated from renewable energy sources can be converted into hydrogen. This approach enables the storage of surplus renewable energy for later use, particularly during periods of low solar or wind availability [1][2]. In the context of the ZEESA project, hydrogen is produced via electrolysis powered exclusively by renewable energy sources (RES), thus qualifying as green hydrogen and ensuring a fully sustainable energy cycle [11].

- **Safety and Chemical Properties:**

Hydrogen possesses several characteristics that enhance its safety and usability across diverse applications. It is colorless, odorless, non-toxic, and—due to its low molecular weight—readily disperses in the event of a leak, reducing the risk of accumulation and ignition. While hydrogen is flammable, appropriate design and safety standards can mitigate associated risks effectively [11].

- **Energy Density and Industrial Relevance:**

Hydrogen exhibits a high specific energy content, making it highly suitable for energy-intensive and industrial processes. Its capability to deliver consistent energy over time enhances its role in long-term storage and base-load applications [4].

- **Public Acceptance and Land Use:**

Compared to large-scale photovoltaic or wind power installations, hydrogen-based systems tend to have a lower visual impact and occupy less physical space. These features can foster greater public acceptance, particularly in sensitive environments such as remote or protected areas [8].

- **Addressing Renewable Intermittency:**

One of the principal challenges associated with renewable energy is its intermittent nature. Hydrogen offers a compelling solution as a long-term energy storage medium, capable of decoupling generation from consumption [4]. This characteristic is especially critical for Arctic and isolated environments, such as the one considered in Phase 4 of the ZEESA project [1].

In this specific application, logistical challenges related to hydrogen transport and distribution are mitigated by the local production and consumption of hydrogen. This closed-loop configuration eliminates the need for complex infrastructure and ensures that energy autonomy can be achieved without compromising efficiency or sustainability [11].

1.4 Objectives of the Proposed Thesis: Phase 4

Phase 4 represents the ultimate and most ambitious goal of the ZEESA project: the development of a fully zero-emission energy system at the Arctic station of Isfjord Radio. This phase aims to completely eliminate the use of fossil fuels—particularly diesel—through the implementation of a hydrogen-based system for long-term energy storage [1][11].

- **Selection of Suitable Hydrogen Technologies:**

The project will identify the most appropriate technologies for hydrogen production, storage, and utilization, with a focus on electrolyzers, fuel cells, and storage systems. This selection will be informed by a comprehensive review of the scientific and technical literature, including case studies of similar projects deployed in remote and climatically extreme environments [11]. The objective is to determine the most reliable, efficient, and scalable solutions for Arctic applications.

- **System Sizing and Energy Autonomy Modeling:**

The hydrogen storage system, the electrolyzer, and the fuel cell will be dimensioned using simulation models developed in Python. The analysis will assess the energy system's capacity to operate in full autonomy—that is, to meet the local energy demand under all operating conditions, including prolonged periods with minimal renewable input. Various operational scenarios and system configurations will be evaluated, incorporating real-world production and consumption data collected during Phases 2 and 3 of the project [1]. The goal is to identify the most technically, logistically, and operationally efficient configuration.

- **Economic Sensitivity Analysis:**

A detailed economic assessment will be conducted to evaluate the financial feasibility of the proposed hydrogen-based solutions. Key variables—such as hydrogen production costs, technology component prices, and operational expenses—will be explored to understand the economic impact of each scenario [4][11]. This analysis will provide evidence-based support for future design choices and policy decisions.

To achieve these objectives, the research will employ advanced simulation tools including Python, MATLAB, and Excel. These platforms will process empirical data gathered in earlier project phases to deliver actionable insights for the design and deployment of a sustainable energy system that can be replicated in other Arctic or remote environments.

2. Technologies Comparison for Hydrogen Production, Utilization, and Storage

2.1 Introduction

Hydrogen has emerged as a critical pillar in the global transition toward a low-carbon economy. As a flexible and clean energy carrier, it plays a central role in enabling the decarbonization of key sectors such as transportation, power generation, and heavy industry. Its integration with renewable energy sources enhances the ability to balance supply and demand by converting surplus electricity into a storable chemical form—a concept commonly referred to as Power-to-Hydrogen (PtH_2) [12].

In renewable-based energy systems, the intermittent nature of solar, wind, and hydroelectric power—collectively referred to as variable renewable energy (VRE)—poses significant challenges to grid stability and energy security. While batteries are effective for short-term storage applications, hydrogen offers a more suitable solution for long-duration and large-scale storage. Its high energy density, versatility in use, and compatibility with existing infrastructure make it a promising candidate for both stationary and mobile energy applications [13].

Hydrogen technologies are a cornerstone of broader Power-to-X (PtX) strategies, where electricity is converted into other energy carriers or synthetic fuels. Among these: Power-to-Gas (PtG) involves the generation of synthetic natural gas or hydrogen; Power-to-Liquid (PtL) enables the production of synthetic fuels such as methanol or dimethyl ether (DME). A typical Power-to-Hydrogen system utilizes electricity—ideally from renewable sources—to drive water electrolysis, producing hydrogen and oxygen. The resulting hydrogen can then be:

- Stored for later use in electricity generation or transport;
- Converted into other chemical products (e.g., ammonia or methane);
- Integrated into a broader PtX supply chain for synthetic fuel production [14].

This chapter provides a comprehensive review and comparison of current technologies for hydrogen production, storage, and utilization, with a particular focus on electrolytic production methods (e.g., PEM and alkaline electrolysis), hydrogen storage solutions (compressed, liquefied, or metal hydride-based), and end-use technologies such as fuel cells. The analysis is grounded in an extensive literature review and is enriched by real-world case studies that demonstrate system performance under diverse environmental and infrastructural conditions [12].

2.2 Electrolyzers

2.2.0 Electrolyzers introduction

An electrolyzer is an electrochemical device that splits water (H_2O) into its constituent elements—hydrogen (H_2) and oxygen (O_2)—through the application of electrical energy. This process, known as water electrolysis, is endothermic and non-spontaneous, meaning it requires an external energy input to proceed. When powered by renewable electricity, the resulting hydrogen is commonly referred to as green hydrogen [15].

The overall electrochemical reaction is as follows:

$$H_2O\ (l) + 237.2\ kJ/mol_{ele}c + 48.6\ kJ/mol_{heat} \rightarrow H_2 + \tfrac{1}{2}\ O_2$$

(Equation 1.1)

This reaction highlights both the electrical and thermal energy requirements for the dissociation of water molecules.

At the core of an electrolyzer are three main components:

- Anode and cathode electrodes, where the oxidation and reduction reactions occur;
- An electrolyte, which allows ionic conduction between the electrodes;
- A separator or membrane, which prevents mixing of the produced gases and ensures system safety and purity.

Electrolyzers are classified based on the type of electrolyte used and the operating temperature of the system. The main technologies currently in use or under development include:

- Alkaline Electrolyzers (ALK)
- Proton Exchange Membrane Electrolyzers (PEM)
- Solid Oxide Electrolyzers (SOEC)
- Proton Conducting Ceramic Electrolysis Cells (PCCEL)
- Anion Exchange Membrane Electrolyzers (AEM) [16]

Each technology has distinct characteristics in terms of:

- Energy efficiency and degradation rate
- Capital and operational costs
- Material compatibility and durability
- Start-up time and load-following capability
- Integration potential with intermittent renewable energy sources

Understanding these differences is essential for selecting the most suitable electrolyzer type in applications ranging from off-grid renewable systems to industrial-scale hydrogen hubs [17].

2.2.1 Alkaline Electrolyzer (AEL)

Alkaline water electrolysis (AWE) is the most established and commercially mature technology for hydrogen production through electrochemical water splitting. Operating typically at temperatures between 65 °C and 100 °C and pressures up to 25–30 bar, alkaline electrolyzers use a liquid electrolyte—usually a 25–30% aqueous solution of potassium hydroxide (KOH)—to facilitate ionic conduction between electrodes [12].

Working Principle and Components

In a typical AEL system, two electrodes (anode and cathode) are immersed in the alkaline solution and separated by a porous diaphragm that allows hydroxide ions (OH^-) to pass while preventing the mixing of hydrogen and oxygen gases. The electrochemical half-reactions are:

- Anode: $4OH^- \rightarrow O_2 + 2H_2O + 4e^-$
- Cathode: $4H_2O + 4e^- \rightarrow 2H_2 + 4OH^-$

The electrodes are typically made from conductive porous metal structures (e.g., nickel or nickel-coated stainless steel), often enhanced with non-precious metal catalysts, such as transition metal oxides, which perform well in the alkaline environment and reduce overall system cost [13].

Materials and Membrane Technology

AELs avoid the use of platinum group metals (PGMs), which significantly reduces their capital expenditure (CAPEX). The diaphragm, historically made from asbestos, is now typically composed of more advanced materials such as Zirfon Perl™—a composite of zirconia and polysulfone—offering good chemical resistance, mechanical strength, and wettability.

While the diaphragm is essential for gas separation, it introduces ohmic resistance, which limits current density and efficiency. Efforts to improve performance include zero-gap cell designs, thinner diaphragms, and better electrode-membrane interfaces [16].

Performance and Limitations

AEL systems are characterized by:

- Lower current densities than PEM or SOEC systems
- Moderate efficiencies (typically 65–75%)
- Slow dynamic response, with start-up times up to 20 minutes
- Limited partial load operation, usually effective between 20–100% of rated capacity
- Hydrogen output at relatively low pressures (generally 0–16 bar; rarely higher)
- Risk of H_2/O_2 gas crossover at high pressure or during load transients, requiring careful system design [15]

These factors make AELs less suitable for direct coupling with intermittent renewable energy sources (e.g., wind or PV), but ideal for stable, baseload applications such as large-scale industrial hydrogen generation, particularly when cost sensitivity is high.

Technical Challenges and R&D Focus

Despite their maturity, AEL technology still faces several technical challenges, including:

- Increasing current density while maintaining acceptable efficiency and durability
- Reducing diaphragm thickness without compromising gas separation

- Enhancing catalyst activity with low-cost, earth-abundant materials
- Improving water management and minimizing ohmic losses
- Integrating with VRE sources through hybrid system designs or buffer storage [17]

Case Studies and Applications

- Arrowsmith Hydrogen Plant (Western Australia): Aims to produce green hydrogen using AELs powered by 70 MW of solar and 96 MW of wind energy. It plans to scale up production from 25 to 300 tons/day [13].
- ELYntegration Project (European Union): A flexible single-stack AEL system capable of producing 4.5 tons/day of hydrogen, specifically engineered to interface with variable renewable sources [14].

2.2.2 Proton Exchange Membrane Electrolyzer (PEM)

Proton Exchange Membrane (PEM) electrolyzers represent a modern and increasingly adopted electrolysis technology, especially suited for dynamic, renewable-powered hydrogen production. Unlike alkaline systems, PEM electrolyzers use a solid polymer electrolyte—typically Nafion®, a sulfonated tetrafluoroethylene-based fluoropolymer—that conducts protons from the anode to the cathode while acting as a physical barrier between the generated gases [12].

PEM systems are characterized by fast dynamic response, high current density, and the ability to operate at high output pressures (30–80 bar, and in some cases up to 130 bar). These features make them highly suitable for smaller-scale, modular, and renewable-integrated applications, despite their higher capital and material costs.

Working Principle and Cell Design

In a PEM electrolyzer, water is fed to the anode side, where it is split into oxygen, protons, and electrons:

- Anode: $2H_2O \rightarrow O_2 + 4H^+ + 4e^-$
- Cathode: $4H^+ + 4e^- \rightarrow 2H_2$

The protons (H^+) migrate through the solid polymer electrolyte, while electrons travel through an external circuit. On the cathode side, the protons recombine with electrons to form high-purity hydrogen gas (>99.99%) [13].

The Membrane Electrode Assembly (MEA) consists of:

- A proton-conducting membrane (~200 μm)
- Catalyst-coated electrodes (iridium oxide at the anode, platinum at the cathode)
- Gas diffusion layers (GDLs)
- Bipolar plates (BPPs) and porous transport layers [16]

Performance Characteristics

PEM electrolyzers offer:

- High current density (>2 A/cm²)
- Fast load-following (start-up in seconds)
- Wide operating range (10–125% of nominal power)
- Pressurized hydrogen output
- High gas purity and low crossover risk

These attributes make PEM ideal for integration with intermittent renewables and for use in constrained, off-grid, or Arctic environments [14].

Material Requirements and Limitations

Challenges include:

- High costs (due to noble metals: platinum, iridium)
- Membrane degradation
- Sensitivity to water purity (needs deionized water)
- Complex balance of plant (BoP), requiring dryers, humidifiers, and safety controls [15]

Research and Development Directions

Future innovations aim to:

- Reduce PGM catalyst loading
- Develop non-PGM alternatives
- Improve membrane durability
- Simplify BoP and stack architecture [17]

Case Studies and Applications

- OffsH2ore Project – Germany
  PEM electrolyzers on offshore wind platforms; targets 50,000 tons/year green hydrogen production. Environment: marine, remote, cold. [16]
- H2Future Project – Austria
  2 MW PEM system producing 300 tons/year powered by hydroelectricity. Location: alpine region with seasonal variability. [13]

2.2.3 Solid Oxide Electrolyzer (SOE)

Solid Oxide Electrolysis Cells (SOECs) represent the most efficient hydrogen production technology currently available, though they remain at an early stage of industrialization. Operating at high temperatures—typically between 700°C and 1,000°C—SOECs use a solid ceramic electrolyte, most commonly yttria-stabilized zirconia (YSZ), to conduct oxygen ions (O^{2-}) across the cell. Unlike low-temperature electrolyzers that split liquid water, SOECs perform electrolysis using steam, achieving electrical efficiencies up to 80–90%, especially when integrated with waste heat recovery systems [18].

Working Principle and Cell Design

Water vapor is introduced at the cathode, where it is reduced to hydrogen and oxide ions:

- Cathode: $H_2O + 2e^- \rightarrow H_2 + O^{2-}$
- Anode: $O^{2-} \rightarrow \frac{1}{2}O_2 + 2e^-$

Typical SOEC architecture includes:

- Ni-YSZ composite cathodes
- Perovskite-based MIEC anodes (e.g., LSM or LSCF)
- YSZ or GDC electrolytes
- Either electrolyte-supported (ESC) or anode-supported (ASC) configurations for thermal and mechanical optimization [19]

Performance Characteristics

SOECs offer:

- Exceptional efficiency
- Fuel flexibility (H_2, CO, syngas, CH_4)
- Reversible operation (fuel cell mode)
- PGM-free design

These characteristics make SOECs attractive for high-demand industrial settings with stable heat availability [20].

Limitations and Technical Challenges

- High capital costs
- Long start-up times
- Poor thermal cycling resistance
- Shorter lifespan (20,000–40,000 h)
- Complex thermal and pressure management
  These limitations restrict their use in variable or remote systems like Arctic microgrids [21].

Research Directions

Ongoing R&D aims to:

- Improve thermal shock resistance
- Extend operational lifespan
- Lower material and stack cost
- Develop modular, scalable system designs [22]

Case Study:

MULTIPLHY Project – The Netherlands

Europe's first multi-MW hydrogen system using SOECs. 2.6 MW capacity, integrated with industrial steam recovery at a refinery. Environment: stable, high-temperature industrial site [23].

Conclusion

SOECs achieve top-tier efficiency but are currently suitable only for stable, heat-integrated environments. Further development is needed before they can be deployed in dynamic or harsh climates such as the Arctic [18][21].

2.2.4 Proton Conducting Ceramic Electrolysis Cells (PCCEL)

Proton Conducting Ceramic Electrolysis Cells (PCCELs) are an emerging high-temperature electrolysis technology that utilizes ceramic materials capable of conducting protons (H^+) to split steam into hydrogen and oxygen. Operating typically in the 400–600 °C range, PCCELs combine many of the efficiency advantages of SOECs with greater material flexibility and lower thermal stress, making them a promising option for integration in industrial and thermally assisted systems [24].

Working Principle and Cell Design

PCCELs operate using steam as feedstock. At the anode, oxygen is released, while protons pass through a dense ceramic electrolyte to the cathode, where they combine with electrons to form hydrogen gas.

The simplified reactions are:

- Cathode: $H_2O + e^- \rightarrow H^+ + OH^- \rightarrow H_2 + O^{2-}$
- Anode: $O^{2-} \rightarrow \frac{1}{2}O_2 + 2e^-$

Typical materials include:

- Proton-conducting ceramics like $BaZrO_3$ or $BaCeO_3$ doped with Y or Gd
- Catalyst layers optimized for high-temp reaction kinetics
- Sealing systems and gas-tight ceramic interfaces for long-term integrity [25]

Performance Characteristics

PCCELs provide:

- High efficiency (thermal + electrical)
- Use of non-noble metals
- Intermediate temperature range with shorter start-up times than SOECs
- Improved potential for co-location with heat-releasing industrial processes [26]

They are especially suitable for:

- Refineries
- Ammonia or fertilizer plants
- Glass and metallurgy sectors

Limitations and Challenges

Key obstacles include:

- Ceramic degradation under redox and thermal cycling
- Complex thermal insulation needs—especially in cold environments like Svalbard
- Low commercial readiness and standardization
- Limited field testing and integration with fluctuating renewable sources [27]

Research and Development Focus

R&D efforts are directed toward:

- Enhancing proton conductivity at lower temperatures
- Improving chemical and thermal stability
- Optimizing electrode–electrolyte interfaces
- Reducing cost through simplified architecture and cheaper materials [28]

Application Potential

PCCELs are ideal where process heat is available. For example:

- Refineries recovering steam from catalytic reactions
- Fertilizer facilities or glassworks with constant high-temperature operation

  These integrations support efficient, decentralized, and low-emission hydrogen generation.

Conclusion

PCCELs offer a promising compromise between low- and high-temperature electrolysis, balancing efficiency with reduced material and thermal demands. Although not yet commercialized, they are well-positioned for industrial deployment and hybrid renewable systems when thermal energy can be harnessed [24][25].

2.2.5 Anion Exchange Membrane Electrolyzer (AEM)

Anion Exchange Membrane Electrolyzers (AEMWE) are a promising new class of water electrolysis systems that combine the benefits of both alkaline and proton exchange membrane technologies. They operate in mildly alkaline environments and use solid polymer membranes that conduct hydroxide ions (OH^-) instead of protons (H^+). This configuration allows the use of non-precious metal catalysts, resulting in lower system costs and environmental impact [29].

Working Principle and Cell Design

In an AEM electrolyzer, water is introduced at the cathode, where it is reduced to form hydrogen gas and hydroxide ions. The OH^- ions pass through the membrane to the anode, where they are oxidized to produce oxygen gas:

- **Cathode**: $4H_2O + 4e^- \rightarrow 2H_2 + 4OH^-$
- **Anode**: $4OH^- \rightarrow O_2 + 2H_2O + 4e^-$

The anion exchange membrane, typically based on quaternary ammonium-functionalized polymers, separates the gas chambers and conducts ions without requiring noble metals like platinum or iridium [30].

AEM cell components generally include:

- Non-PGM catalysts (e.g., Ni, Co, Mn)
- Gas diffusion layers (GDLs)
- Mildly alkaline operating environments (pH ~9–11)
- Modular stack architecture, supporting scalable deployment

Performance Characteristics

Key advantages of AEMWE systems include:

- Reduced material cost due to non-precious metals
- Moderate operating temperatures (25–70 °C)
- Fast dynamic response, compatible with variable renewable inputs
- High gas purity and compact system design
- Efficiencies in the range of 65–75%
- Lifetimes estimated between 20,000 and 60,000 hours [29][31]

These characteristics make AEMWE well-suited for mid-scale renewable applications and decentralized hydrogen generation.

Limitations and Technical Challenges

Despite their potential, AEMWE systems face several limitations:

- Membrane durability issues (e.g., carbonation, oxidation)
- Lower hydroxide ion conductivity than proton membranes
- Degradation under variable load and environmental stress
- Lack of extensive field testing, particularly in extreme or remote environments [32]

R&D efforts are currently focused on:

- Stabilizing membrane chemistry for long-term use
- Enhancing catalyst activity and electrode–membrane bonding
- Improving mechanical and chemical robustness
- Developing containerized or off-grid-ready systems

Application Potential and Case Study

Offshore Wind Hydrogen Production Project (USA)

A U.S. Department of Energy-backed initiative is currently testing AEM electrolyzers in harsh marine environments powered directly by offshore wind. The system is designed for modular deployment, cold tolerance, and zero-noble-metal operation—making it a candidate for Arctic or remote installations [33].

Conclusion

AEMWE technology offers a compelling balance between cost, performance, and sustainability. While still under development, it holds strong potential for Arctic and off-grid renewable hydrogen systems—especially where PEM costs are prohibitive, and AEL is impractical due to dynamic or cold climate conditions [29][30][33].

2.2.6 Comparison for Arctic Application

The deployment of electrolyzer technologies in remote, cold environments such as the Svalbard archipelago must consider various critical factors, including temperature extremes, intermittent renewable energy input, logistical constraints, and the need for high reliability and low maintenance [34].

Technology	Initial Cost	Efficiency	Lifetime	Fast Response	RES Compatibility	H_2 Purity
AEL	▯ Low	▯ Medium (65–75%)	▯ >60,000 h	🔴 No	🔴 Limited	▯ Medium
PEM	🔴 High	▯ High (70–83%)	▯ 50,000–80,000 h	▯ Yes	▯ High	▯ High
AEM	▯ Medium	▯ Medium (65–75%)	▯ 20,000–60,000 h	▯ Yes	▯ High	▯ High
SOE	🔴 High	▯ Very High (80–90%)	🔴 20,000–40,000 h	🔴 No	🔴 No	▯ Medium

Table 1: Summary of Electrolizer

1. Alkaline Electrolyzer (AEL)
Advantages: Mature and cost-effective; long lifespan; uses abundant, inexpensive materials.
Limitations: Poor load-following capability; slow startup; electrolyte freezing risk in Arctic; limited compatibility with renewables.
Svalbard Relevance: Attractive for stable baseload, but requires thermal management and storage buffers due to freezing risk and slow dynamics [35].

2. Proton Exchange Membrane Electrolyzer (PEM)
Advantages: High efficiency and purity; fast response; operates at pressure; compact design; resilient to cold.
Limitations: High CAPEX; sensitive to feedwater purity; shorter lifespan than AEL.
Svalbard Relevance: Best-suited for Arctic settings due to flexible dynamics, cold operation, and modularity—demonstrated in projects like the Haeolus Project in northern Norway [36][37].
Tabella 2:Summary of Fuel Cell

3. Anion Exchange Membrane Electrolyzer (AEM)
Advantages: PGM-free; moderate temperature operation; flexible and low-cost; compact and efficient.
Limitations: Under development; membrane stability and durability concerns; limited real-world validation.
Svalbard Relevance: Promising for mid-term deployment—if field-tested and optimized for Arctic conditions, it could become a viable PEM alternative [38].

4. Solid Oxide Electrolyzer (SOE)
Advantages: Highest efficiency; reversible operation; no precious metals; excellent for industrial-scale use.
Limitations: High temperature; slow dynamics; poor thermal cycling; requires waste heat; atmospheric pressure output.
Svalbard Relevance: Impractical due to lack of stable heat source and complex thermal insulation requirements. Best reserved for industrial settings with available heat [39].

Conclusion and Recommendations
In the context of the Svalbard Islands, where energy systems must endure:

- Harsh climate,
- Renewable intermittency,
- Limited infrastructure access,

PEM electrolyzers are the optimal choice. Despite their cost, they offer unmatched:

- Rapid load responsiveness,
- Cold-weather resilience,

- Renewable integration performance,
- High-purity hydrogen output.

AEL systems are reliable and affordable but limited by freezing risk and poor load response.
AEM systems, while not yet fully mature, show excellent potential for Arctic microgrids. Continued R&D could position them as PEM alternatives in the near future.
SOE systems, despite record efficiencies, are unsuitable for cold and variable environments due to their heat dependence and operational inflexibility [34][35][36][37][38][39][40].

2.3 Fuel Cell Technologies

2.3.0 Fuel Cells

Fuel cells are electrochemical devices that convert hydrogen (H_2) directly into electricity, emitting only water (H_2O) and heat as by-products. The fundamental redox reactions are:
Anode: $H_2 \rightarrow 2H^+ + 2e^-$ [41]
Cathode: $\frac{1}{2}O_2 + 2H^+ + 2e^- \rightarrow H_2O$ [41]
Overall: $H_2 + \frac{1}{2}O_2 \rightarrow H_2O$ + Electricity + Heat [41]
Fuel cells consist of:

- Anode and cathode electrodes where the redox reactions occur;
- An electrolyte that ensures ion conduction;
- A membrane that prevents gas mixing and guarantees system safety [41].

Fuel cells are categorized by electrolyte type and operating temperature. The main variants include:

- PEMFC – low-temp, fast-start systems for transport/portable use;
- SOFC – high-temp, efficient cells for industrial power;
- AFC – used in aerospace, high efficiency at moderate temps;
- PAFC – tolerant to impurities, used for stationary CHP;
- MCFC – suitable for large-scale power from hydrocarbon fuels [42][43].

Each fuel cell type varies in efficiency, durability, cost, start-up time, and integration with hydrogen supply and renewables [44].

2.3.1 Proton Exchange Membrane Fuel Cells (PEMFC)

PEMFCs are among the most advanced and widely deployed hydrogen fuel cell technologies. They operate at low temperatures (50–80 °C) using a solid polymer electrolyte membrane—typically Nafion®—to transport protons from anode to cathode [41][45].
Working Principle and Cell Design
Anode: $H_2 \rightarrow 2H^+ + 2e^-$
Cathode: $\frac{1}{2}O_2 + 2H^+ + 2e^- \rightarrow H_2O$ [41]
The MEA consists of:

- Proton-conducting membrane (~50–200 μm);
- Platinum-based catalysts;
- Gas Diffusion Layers (GDLs);
- Bipolar plates (BPPs) for current collection and fluid distribution [41][45].

Performance Characteristics

- High power density (1.0–2.0 W/cm²)
- Efficiency: ~50–60%
- Lifetime: 20,000–40,000 hours
- Pressure: 1–3 bar
- Fast response and modular design
- Zero emissions (when powered by green H_2) [41][45]

Limitations

- Requires >99.999% pure H_2
- High cost due to PGM catalysts
- Membrane degradation and water management issues [41][44]

Application and Case Study

- Use cases: transport, micro-CHP, Arctic microgrids
- Haeolus Project (Norway): PEMFC integrated with wind, cold-climate tested [46]
- Toyota Mirai: commercial vehicle with >500 km range and 114 kW output [47]

Conclusion

PEMFCs offer unmatched flexibility and are ideal for cold, remote, and dynamic applications despite material cost and hydrogen purity limitations [41][44].

2.3.2 Solid Oxide Fuel Cells (SOFC)

SOFCs operate at high temperatures (700–1,000 °C) using solid ceramic electrolytes (e.g., YSZ) to transport O^{2-} ions. They achieve high efficiencies, especially in CHP setups [48].

Working Principle and Cell Design

Cathode: $O_2 + 4e^- \rightarrow 2O^{2-}$

Anode: $H_2 + O^{2-} \rightarrow H_2O + 2e^-$ [41]

Key components:

- Ni-YSZ anodes
- Perovskite cathodes (e.g., LSCF)
- Dense YSZ electrolyte
- Stack formats: electrolyte-supported and anode-supported [41]

Performance Characteristics

- Efficiency: 60–65% (85% CHP)
- Long lifespan (40,000–80,000 h)
- Fuel flexibility: H_2, CH_4, biogas
- No need for PGM catalysts [41][48]

Limitations

- Long start-up time and thermal cycling issues
- Complex thermal management
- Not suitable for intermittent renewables [44]

Application and Case Study

- Bloom Energy Servers (USA): 60%+ efficiency in tech campuses [49]

Conclusion

SOFCs offer unparalleled efficiency for industrial and stationary power, though their high-temperature operation limits mobile or Arctic use [44].

2.3.3 Alkaline Fuel Cells (AFC)

AFCs operate with aqueous KOH electrolytes at 60–90 °C. They are efficient and historically used in space missions (e.g., NASA Apollo) [50].

Working Principle and Cell Design

Anode: $H_2 + 2OH^- \rightarrow 2H_2O + 2e^-$

Cathode: $\frac{1}{2}O_2 + H_2O + 2e^- \rightarrow 2OH^-$ [41]

Features:

- Carbon or nickel electrodes
- PGM-free catalysts possible
- Electrolyte recirculation and gas management systems [41]

Performance Characteristics

- Efficiency: ~60%
- Fast kinetics and startup
- Lifespan: ~5,000–15,000 h [50]

Limitations

- Highly sensitive to CO_2 (electrolyte degradation)
- Requires pure gases
- Low commercial viability for ambient use [44]

Application and Case Study

- NASA Apollo: High efficiency under controlled conditions
- Use cases: spacecraft, submarines, closed-loop systems [50]

Conclusion

AFCs provide high efficiency in sealed environments but are unsuitable for open-air or Arctic deployment due to CO_2 sensitivity [44].

2.3.4 Phosphoric Acid Fuel Cells (PAFC)

PAFCs use liquid phosphoric acid as electrolyte and operate at 150–200 °C. They are resilient to fuel impurities and often used in CHP [41].

Working Principle and Cell Design

Anode: $H_2 \rightarrow 2H^+ + 2e^-$

Cathode: $\frac{1}{2}O_2 + 2H^+ + 2e^- \rightarrow H_2O$ [41]

Features:

- Platinum catalysts
- Graphite-based electrodes
- Heat exchangers for CHP [41][48]

Performance Characteristics

- Efficiency: 40–50% (up to 85% CHP)
- Lifespan: 40,000–60,000 h
- Impurity-tolerant [48]

Limitations

- Low power density
- Acid handling and slow startup
- Large system footprint [44]

Application and Case Study

- ONERGY Plant (Seoul): 11 MW PAFC for buildings
- Use cases: hospitals, backup power, CHP [48]

Conclusion

PAFCs are reliable for long-duration stationary power, but limited in mobility due to cost and size [44].

2.3.5 Molten Carbonate Fuel Cells (MCFC)

MCFCs operate at 600–700 °C using molten carbonate salts to conduct CO_3^{2-}. They support direct hydrocarbon use and large-scale CHP [49].

Working Principle and Cell Design

Anode: $H_2 + CO_3^{2-} \rightarrow H_2O + CO_2 + 2e^-$

Cathode: $CO_2 + \frac{1}{2}O_2 + 2e^- \rightarrow CO_3^{2-}$ [49]

Characteristics:

- High-temperature operation
- Internal reforming of methane or biogas
- Nickel or stainless steel-based components [49]

Performance Characteristics

- Efficiency: 50–60% (85% CHP)
- Fuel flexibility
- MW-scale output
- Lifespan: ~20,000–40,000 h [49]

Limitations

- Complex corrosion control
- Thermal stress and slow startup
- Costly maintenance [49]

Application and Case Study

- FuelCell Energy (California): 2.8 MW MCFC on biogas [49]
- Use cases: utility-scale power and CHP plants

Conclusion

MCFCs are best suited for industrial baseload power with stable, high-temperature conditions [44].

2.3.6 Comparison for Arctic Application

Technology	Temp	Efficiency	Fuel Flexibility	Power Density	Start-Up Time	Best Use Case
PEMFC	□ Low (50–80 °C)	□ Medium (50–60%)	🔴 Low (pure H_2)	□ High	□ Fast	Arctic, transport, portable
SOFC	🔴 High (700–1,000 °C)	□ Very High (60–85%)	□ High (CH_4, syngas)	□ Medium	🔴 Slow	CHP, industry
AFC	□ Medium (60–90 °C)	□ High (~60%)	🔴 Low (pure O_2, H_2)	□ Medium	□ Medium	Aerospace, sealed systems
PAFC	□ Medium (150–200 °C)	□ Medium (40–50%)	□ Medium (reformed H_2)	🔴 Low	□ Medium	Buildings, CHP
MCFC	🔴 High (600–700 °C)	□ High (50–85%)	□ High (CH_4, syngas)	□ Medium	🔴 Slow	Industrial, utility-scale

Table 2 :Summary of Fuel Cell

Conclusion and Recommendations
Fuel cells provide clean, efficient electricity from hydrogen. In Arctic and off-grid contexts:

- PEMFCs are the top choice for fast response, low-temperature operation, and modularity.
- SOFCs are ideal in CHP or waste heat applications but unsuitable for dynamic Arctic systems.
- AFCs and PAFCs work in niche controlled settings but not viable for open deployment.
- MCFCs support large-scale hydrogen or biogas power but need stable, high-temperature environments.

Continued innovation, particularly in PEMFC catalysts and durability, is key to expanding Arctic deployment [44].

2.4 Hydrogen Storage Technologies

2.4.0 Introduction

*Hydrogen is increasingly recognized as a pivotal element in the transition to a sustainable energy system, primarily due to its ability to store energy from intermittent renewable sources such as wind and solar. However, one of the critical challenges in the hydrogen economy is its storage. Owing to its low volumetric energy density under ambient conditions (0.0899 kg/m^3), hydrogen requires specific storage technologies to become viable for practical applications [51]. These technologies aim to enhance the energy density, safety, efficiency, and cost-effectiveness of hydrogen storage **systems.***

Hydrogen storage can be classified into four principal categories:

- compressed hydrogen gas
- liquid hydrogen
- metal hydrides

- chemical hydrogen carriers

Each technology is characterized by distinct advantages and disadvantages, depending on the application context, operational requirements, and economic constraints [51]. This chapter provides an in-depth technical analysis of each storage method, including their operating principles, performance metrics, real-world applications, and comparative evaluation.

2.4.1 Compressed Hydrogen Storage

Compressed hydrogen storage involves physically storing hydrogen gas under high pressure, typically ranging between 350 to 700 bar. This method requires pressure-resistant containers made from composite materials, often involving carbon fiber-reinforced polymers [52]. The gas is usually compressed at the electrolyzer output pressure (e.g., 30-35 bar) and may require further compression for specific applications, such as mobility or high-capacity storage systems.

The design includes pressure vessels, safety valves, gas monitoring systems, and thermal management mechanisms. The tanks are categorized into different types (Type I to Type IV) based on their material composition and allowable operating pressures [52].

Advantages:

- High technological maturity and commercial availability
- Simple and modular design enables scalability
- Fast hydrogen charge and discharge rates
- Compatible with decentralized refueling infrastructures
- Minimal energy losses during storage phase

Disadvantages:

- High compression energy requirements reduce round-trip efficiency
- Storage vessels must withstand high pressure, raising safety and cost concerns
- Lower volumetric energy density compared to liquid or solid-state options
- Risk of hydrogen leakage and associated safety hazards [52]

Case Studies: Compressed hydrogen is widely used in hydrogen fuel cell vehicles (e.g., Toyota Mirai, Hyundai Nexo), as well as in decentralized refueling stations and off-grid renewable installations. For example, the REMOTE project initially utilized compressed storage at 28 bar to store 50 kg of hydrogen [53].

Conclusion:
Compressed hydrogen storage is a well-established, flexible solution suited for both stationary and mobile applications. While it requires significant safety infrastructure and incurs energy penalties for compression, its simplicity and compatibility with current technology make it a go-to choice for early-stage hydrogen deployment [52][53].

2.4.2 Liquid Hydrogen Storage

Liquid hydrogen (LH2) storage involves cooling gaseous hydrogen to cryogenic temperatures below -253°C, where it condenses into a liquid form. This method significantly increases hydrogen's volumetric energy density [54].

The infrastructure includes cryogenic tanks with multilayer vacuum insulation, boil-off mitigation systems, and liquefaction units. The liquefaction process consumes 30-40% of the hydrogen's higher heating value (HHV) [54].

Advantages:

- Highest volumetric energy density among storage methods
- Eliminates the need for high-pressure tanks
- Suitable for large-scale, long-distance transportation
- Compatible with aerospace and maritime hydrogen applications

Disadvantages:

- Requires expensive cryogenic infrastructure
- High energy losses due to liquefaction and boil-off
- Higher operational and capital costs compared to compressed storage
- Safety risks associated with cryogenic temperatures and pressure build-up

Case Studies:
LH2 is extensively used by aerospace agencies such as NASA for rocket propulsion [55]. Projects like H2Ships and hydrogen export initiatives in Australia and Japan consider LH2 for maritime and cross-continental transport [55].

Conclusion:
While liquid hydrogen storage offers the highest volumetric energy efficiency, its deployment is currently limited to specialized sectors due to high costs and infrastructure complexity.

2.4.3 Metal Hydride Storage

Metal hydride storage is based on the reversible chemical reaction between hydrogen and metal alloys. Common materials include LaNi5H6 and TiFeH2. These materials operate at low pressures (1-30 bar) and near-ambient temperatures. Thermal management systems control the heat generated or consumed during hydrogen absorption and release [56].

Advantages:

- High volumetric energy density
- Low operational pressure enhances safety
- Long-term stability and cycling durability

- Can utilize waste heat from fuel cells or other devices
- Compact design for stationary applications

Disadvantages:

- Low gravimetric energy density limits mobile applications
- High weight of storage system
- Complex thermal management requirements
- Slow absorption/desorption kinetics [56]

Case Studies:

- Phi Suea House (Thailand): Off-grid hydrogen system with metal hydride storage [57]
- HyCARE Project: Integration of PEM electrolyzer, PCM-based heat storage, and fuel cell [57]
- REMOTE (Isola di Ginos): Evaluates transition from compressed gas to metal hydride for microgrid storage [53]

Conclusion:
Metal hydride storage offers a safe, efficient, and compact solution for stationary hydrogen systems, particularly in remote or thermally-integrated microgrids.

2.4.4 Chemical Hydrogen Storage (LOHCs and Hydrides)

Chemical hydrogen storage involves binding hydrogen to a chemical carrier. LOHCs store hydrogen in organic molecules like dibenzyltoluene, later releasing it via catalytic dehydrogenation [58].

These systems require reactors, catalysts, and thermal energy. They operate under moderate pressures and ambient temperatures.

Advantages:

- Hydrogen stored in stable liquid phase
- Compatible with existing fuel infrastructure
- High safety and low volatility
- Scalable for industrial and long-distance transport

Disadvantages:

- High energy requirements for hydrogen release
- Catalyst degradation and solvent recycling costs
- Lower system efficiency

- Still under pilot or demonstration phase

Case Studies:

- HydroGOLIATH Project: LOHC integration with on-board hydrogen systems [59]
- HySTOC Project: Use of LOHCs for hydrogen logistics in Northern Europe [59]

Conclusion:
Chemical hydrogen carriers like LOHCs present a promising avenue for scalable hydrogen storage, particularly in long-distance transportation.

2.4.5 General Conclusion

Technology	Energy Density	Cost	Safety	Efficiency	Scalability	Best for
Compressed H_2	□ Medium	□ Low	□ Medium	□ High	□ High	Mobility, refueling stations, short-term storage
Liquid H_2	□ High	🔴 High	□ Medium	🔴 Low	□ Medium	Aerospace, heavy transport, long-distance transport
Metal Hydrides	□ High (volumetric)	□ Medium	□ High	□ Medium	🔴 Low	Stationary storage, renewable energy integration
Chemical Storage	□ Medium	🔴 High	□ High	🔴 Low	□ High	Long-distance transport, large-scale storage

Table 3:Summary of H2 storage

The choice of hydrogen storage technology depends heavily on the specific use case. Compressed hydrogen is the most practical for mobility and decentralized refueling. Liquid hydrogen is indispensable in aerospace. Metal hydrides provide superior safety and are ideal for thermally integrated, stationary systems. Chemical storage technologies like LOHCs offer a forward-looking solution for global hydrogen logistics[56][58]. However, given that the Svalbard archipelago is uninhabited during the winter months, it was decided to employ a PEM electrolyzer capable of directly producing compressed hydrogen. As a result, the hydrogen storage system will consist of compressed hydrogen at a pressure of 30 bar, with no need for higher-pressure storage.

3. Technical Description of the Isfjord Radio System

This section presents the technical description of the Isfjord Radio system in its current configuration. Phases 1 and 2 of the system have already been completed and are fully operational, while Phase 3 is currently under development.

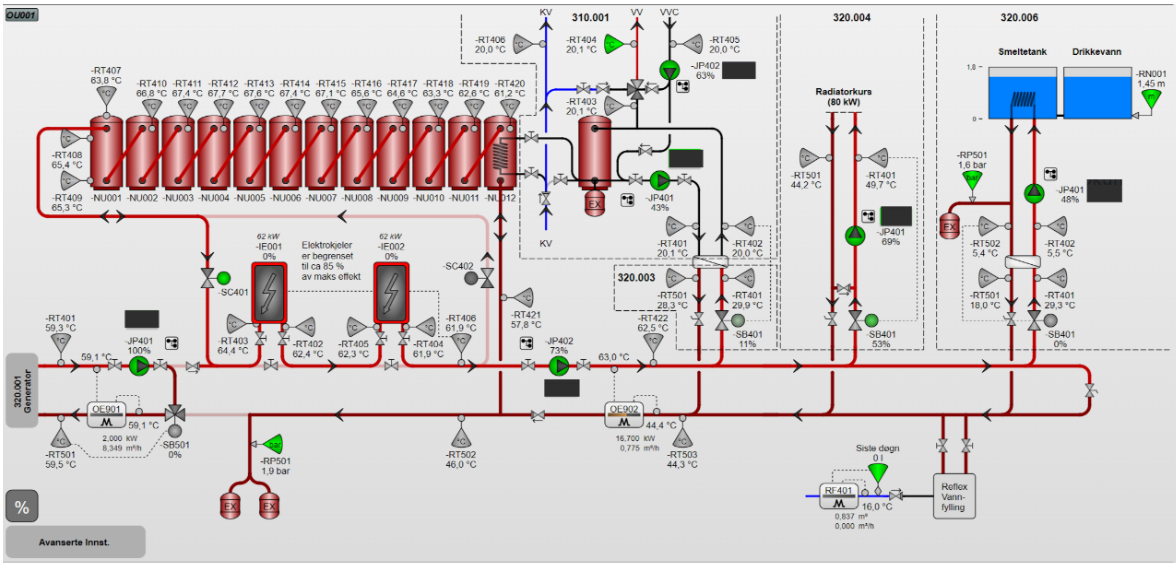

Figure 2: Current installation at Isfjord Radio

3.1 Thermal Production and Storage

The centralized heating system at Isfjord Radio, located in the harsh Arctic environment of the Svalbard archipelago, is designed to ensure high reliability, energy efficiency, and autonomous operation. The system, referred to as *varmeanlegg*, integrates insulated thermal storage tanks, electric boilers, heat exchangers, and a fully automated control system to fulfill three primary thermal functions: space heating, domestic hot water production, and snow melting for water generation [60][61].
At the heart of the heating plant are twelve thermally insulated storage tanks (designated NU001 to NU012), each maintained at approximately 63–64 °C. These tanks function as thermal buffers—accumulating heat during periods of low demand and releasing it during peak loads—thereby improving operational flexibility and reducing system intermittency [61].
Thermal energy is produced by three high-capacity electric resistance boilers (*elektrokjeler*), which are automatically activated based on load demand. Each unit is equipped with a built-in regulation system capable of staged operation and power modulation. This configuration enables responsive and efficient thermal management while reducing peak electrical demand [61].

3.2 Heat Distribution Network

The generated thermal energy is distributed through three independent circuits:

- **Radiator Loop (Radiatorkurs – 320.004):** This loop, with a rated capacity of 80 kW, supplies space heating to the facility. Heat flow is regulated by modulating circulation pumps and motorized valves governed by PID controllers, maintaining a target supply temperature (e.g., 44.2 °C).
- **Snow Melting Circuit (Smeltetank – 320.006):** This subsystem is dedicated to melting snow into potable water. Heat exchangers isolate the heating fluid from the meltwater tank, ensuring hygienic and precisely controlled heat transfer.

- **Domestic Hot Water (Drikkevann):** Domestic hot water is prepared using secondary heat exchangers and stored in thermally insulated tanks. Circulation pumps (e.g., JP401, JP402) ensure constant recirculation to reduce thermal losses [60].

3.3 Instrumentation and Control

A centralized Human-Machine Interface (HMI) oversees system operation, enabling real-time monitoring and fine-tuned parameter control. The control system manages the following key functions:

- Temperature setpoints for each thermal circuit
- Differential temperature regulation
- Scheduling and modulation of boiler operation
- Alarm threshold configuration and seasonal compensation

Each subsystem includes independent programmable controllers, supported by a suite of sensors (e.g., RT401, RT406) and flow meters. This modular design guarantees fail-safe operation and robust system resilience [61].

3.4 Electrical and Thermal Demand Management

Electrical Demand:
Isfjord Radio operates entirely off-grid, with electrical demand met by diesel generators (e.g., SB501). These generators supply power to the electric boilers, pumps, control units, and auxiliary systems. Generator operation is optimized through dynamic load management by the energy management system (EMS), improving fuel efficiency and operational stability [60][62].

Thermal Demand:
Thermal loads are met using a hierarchical control strategy. During periods of low demand, the electric boilers charge the thermal storage tanks. Stored heat is then dispatched to meet demand across the three thermal circuits. This buffer-based logic decouples heat generation from real-time consumption, thereby increasing system efficiency. Heat exchangers and motorized valves, regulated via real-time feedback, ensure appropriate flow and temperature control [61].

3.5 Renewable Integration and Battery Energy Storage

Solar Photovoltaic Panels:
Photovoltaic arrays are planned for rooftop and ground-mount installations. Due to the high-latitude location, bifacial panels and tilt-optimized structures will be employed to maximize solar gain. While solar input is seasonal, it plays a crucial role in providing autonomy during summer months [60].

Wind Turbines:
Given the strong and consistent wind potential in the region, cold-climate horizontal-axis (HAWT) or vertical-axis (VAWT) wind turbines will be installed. These units will provide a significant portion of the annual energy supply, particularly during the polar night when solar availability is negligible [60][62].

Battery Energy Storage System (BESS):
A TESVOLT TSHV high-voltage lithium-ion battery system is being integrated to enable short-term load shifting and grid-forming capabilities. The system consists of three battery units, each with a capacity of 76 kWh. It supports bidirectional energy flow, state-of-charge (SOC) management, and seamless integration with diesel and renewable sources [63].

Battery State-of-Charge parameters:

- SOC min: 20% (threshold to initiate generator startup)
- SOC max: 90% (threshold to terminate generator operation)
- SOC low: 10% (inverter shutdown safety threshold)

3.6 Phase 4 – Base Case Configuration

This section outlines the future development of the Isfjord Radio energy system under Phase 4, focusing on the baseline scenario in which hydrogen is directly produced and stored using a Proton Exchange Membrane (PEM) electrolyzer and reconverted into electricity via a PEM fuel cell.
The proposed configuration, referred to as *Base configuration*, represents a simplified yet robust hydrogen-based system concept. It is designed to assess the feasibility of achieving full energy autonomy in a remote, off-grid Arctic setting. The core design principle is the use of a PEM electrolyzer capable of generating hydrogen at a nominal pressure of approximately 30 bar, thereby eliminating the need for additional compression stages. This approach reduces overall system complexity, maintenance requirements, and parasitic energy losses.
In this scenario, the hydrogen is stored in its directly pressurized form, without any further physical or chemical modification. Such a configuration offers an operationally streamlined solution for integrating hydrogen within an isolated microgrid.

The aim of this simulation phase is to verify whether the site's total energy demands—both electrical and thermal—can be reliably satisfied using exclusively on-site renewable energy sources (i.e., photovoltaic and wind power). The analysis will include:

- Dimensioning of the PEM electrolyzer and PEM fuel cell to meet the annual energy demand;
- Assessment of the maximum hydrogen production rate required to ensure energy continuity during peak renewable output;
- Determination of the total hydrogen storage capacity needed to buffer both seasonal and intraday variability;
- Evaluation of the physical footprint and economic costs associated with implementing compressed hydrogen storage at the specified pressure.

This case study serves as a preliminary boundary condition to evaluate the technical and economic viability of hydrogen-based energy self-sufficiency. If positive, the findings will establish the reference scenario for future comparative analyses, including hybrid system architectures integrating battery storage, alternative electrolyzer technologies, or enhanced thermal recovery schemes.
Under this configuration, the PEM electrolyzer will utilize surplus energy from the photovoltaic and wind generation systems to produce hydrogen. A PEM fuel cell will reconvert stored hydrogen into electricity during periods of low renewable availability. The waste heat recovered from fuel cell operation—up to 60% of the input energy—will be reintegrated into the existing thermal network [60][64].

Thermal Demand Satisfaction
The original thermal infrastructure—including storage tanks and distribution loops for space heating, potable water, and snow melting—will remain in use. However, the electric resistance boilers will be relegated to a backup role, providing supplemental heat only when required. The primary thermal inputs will consist of:

- Waste heat recovered from the PEM fuel cell;
- Direct electric heating supplied by renewable or battery power;
- Thermal energy recovered from the operation of battery management systems [60][63].

This multi-source thermal supply architecture is designed to reduce boiler reliance and increase overall system resilience, especially under variable weather conditions.

Control Architecture and Energy Management System (EMS)
The entire system will be coordinated by a centralized Energy Management System (EMS), responsible for dynamic optimization of energy flows. The EMS will manage:

- Forecasting of renewable energy production;
- Charging and discharging cycles of the battery energy storage system (BESS);
- Hydrogen production, storage, and fuel cell utilization;
- Thermal flow regulation via heat exchangers, including temperature setpoints;
- Load prioritization between critical and deferrable subsystems.

By continuously adapting to real-time environmental conditions, storage states, and demand profiles, the EMS ensures optimal dispatch of resources, maximizing renewable energy utilization and guaranteeing energy security for the remote site [60][62].

4 DATA

Renewable energy (RES)

- **Solar power**

Due to ongoing operational issues with the inverter system, measured solar production data from the photovoltaic array installed at Isfjord Radio are currently unavailable. As a result, solar energy input for simulation and design purposes has been modeled using proxy data from a comparable system in a similar Arctic environment.

Specifically, the production profile of the “Solpark Isfjord Radio” installation—rated at 200 kWp, with a 45° tilt angle and located near Longyearbyen—has been adopted as the reference dataset. This dataset covers the year 2023 and consists of hourly feed-in energy values provided by SINTEF (Foundation for Scientific and Industrial Research).

This proxy-based approach ensures that the simulation reflects realistic environmental conditions and seasonal variability typical of high-latitude solar energy systems. Despite the lack of site-specific measurements, the assumption is considered conservative and of site-specific measurements, the assumption is considered conservative and technically appropriate for a preliminary feasibility assessment.

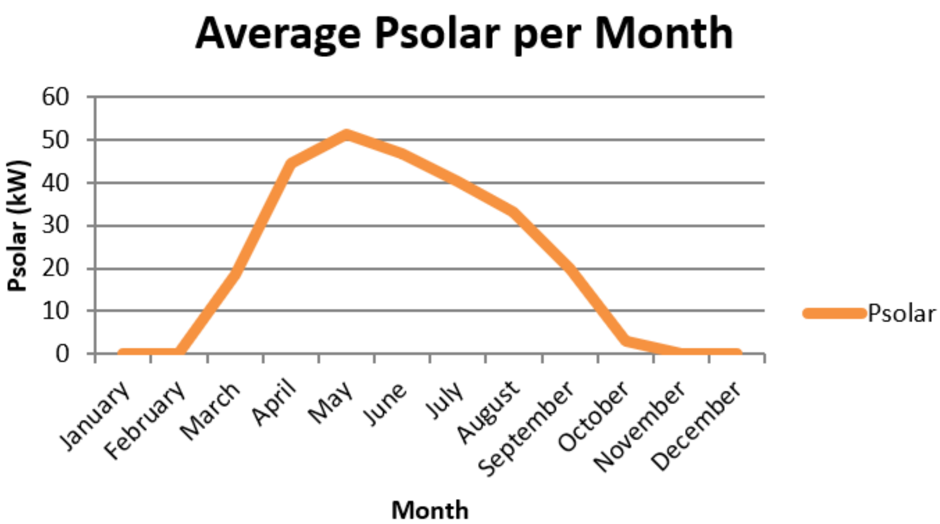

Figure 3:Solar Power

- **Wind power**

As the wind power system is currently in the design phase, no empirical production data are yet available. Therefore, the expected electricity generation from wind has been modeled based on a hypothetical configuration, aligned with the preliminary planning outlined in Phase 3 of the project.

The simulation assumes the deployment of a single wind turbine ($n = 1$) with a nominal rated power of 25 kW. To characterize the wind potential at the site, the capacity factor (Cp) was estimated as the average over a 12-year period (2012–2022), using wind speed data recorded by local meteorological stations in the vicinity of Isfjord Radio.

The resulting forecast represents a plausible long-term average of wind energy yield and is illustrated in the figure below. It should be emphasized that these values are preliminary projections, intended primarily for early-stage system sizing and feasibility analysis. Final system specifications will be refined as the project progresses and as more detailed, site-specific wind assessments become available.

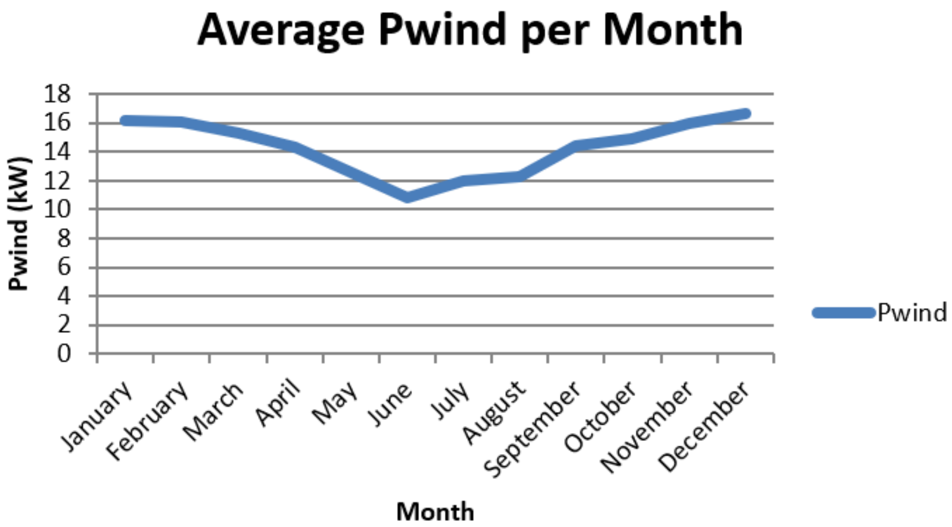

Figura 4: Wind power_1 turbine

Energy Demand Data – Electricity and Heat Consumption

The analysis of the system's energy demand is based on datasets corresponding to the years 2021, 2022, and 2023. These data were:

Processed to generate an hourly time series, allowing for a high-resolution assessment of both electrical and thermal demand profiles;

Harmonized and aligned with the renewable energy production datasets to enable direct comparison. This step included the application of correction factors to account for system efficiencies and distribution losses.

The raw data were provided by SINTEF as part of the Phase 2 monitoring activities and include the following variables:

- Battery charge and discharge cycles
- Electrical consumption
- Electrical production from Diesel Generators 1 and 2
- Thermal consumption
- Thermal production

- **Thermal Load (Qload)**

For the assessment of thermal energy demand, the dataset from the year 2022 was selected as the reference due to its higher completeness and internal consistency relative to the other years in the dataset.

Thermal consumption values represent the aggregate energy demand associated with the following end uses:

- Space heating via radiator systems

- Domestic hot water (DHW) production

- Snow melting for freshwater generation

These integrated values were directly incorporated into the modeling framework to represent realistic thermal demand scenarios under Arctic climatic and operational conditions.

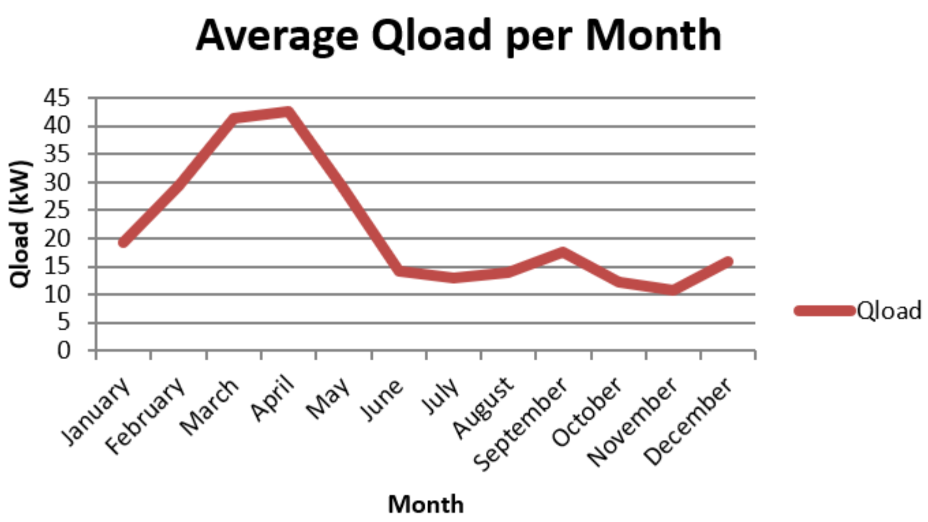

Figure 5: thermal load

- **Eload**

The estimation of the actual electrical load, denoted as E_load, required a detailed analysis, as the variable "electricity consumption" provided in the raw dataset does not directly reflect the real user demand. Instead, it represents the total electricity drawn from the system, which includes both end-user consumption and the electricity used to operate the electric boilers. This relationship can be expressed as:

$$E\_consumption = E\_load + E\_boiler$$

To isolate E_load, it was therefore necessary to estimate the electrical consumption of the electric boilers (E_boiler), which in turn required a thermal analysis of the energy exchanges occurring in the thermal storage tanks.

The thermal energy stored or released by the system was estimated using temperature data recorded for the 12 thermal storage tanks. The following assumptions and parameters were applied:

- Water mass per tank: 100 kg
- Total water mass: 100 kg × 12 = 1,200 kg
- Specific heat capacity of water: cp = 1.6 Wh/kg·K

- Temperature variation per time step:
  $\Delta T = (T\_upper - T\_bottom) / 12$
- Thermal energy variation:
  $Q\_tank = \Delta T \times cp \times m\_H2O$

Temperature measurements were taken every three hours. To obtain an hourly resolution, the calculated thermal energy variation was approximated by dividing each 3-hour value by 3:$Q\_tank\_hourly = Q\_tank\_3h / 3$

The sign of Q_tank provides insight into the system's operational state:
- If $Q\_tank > 0$: Heat production exceeds thermal demand; the surplus energy is stored in the tanks.
- If $Q\_tank < 0$: Heat production is insufficient; energy is extracted from the tanks, and additional thermal demand is likely met by activating the electric boilers.

The total thermal energy that must be supplied by the electric boilers is given by:

$$Q\_boiler = Q\_tank + Q\_thermal\ consumption$$

Assuming an average boiler efficiency of 90%, the corresponding electrical energy consumed by the boilers is calculated as:

$$E\_boiler = Q\_boiler / \eta\_boiler = Q\_boiler / 0.9$$

Having determined E_boiler, the actual electrical load attributable to user devices and services—excluding energy used for thermal purposes—can finally be computed as:

$$E\_load = E\_consumption - E\_boiler$$

This refined calculation enables a more accurate representation of the electrical demand profile, which is critical for the optimal dimensioning of key system components such as fuel cells and electrolyzers in subsequent simulation scenarios.

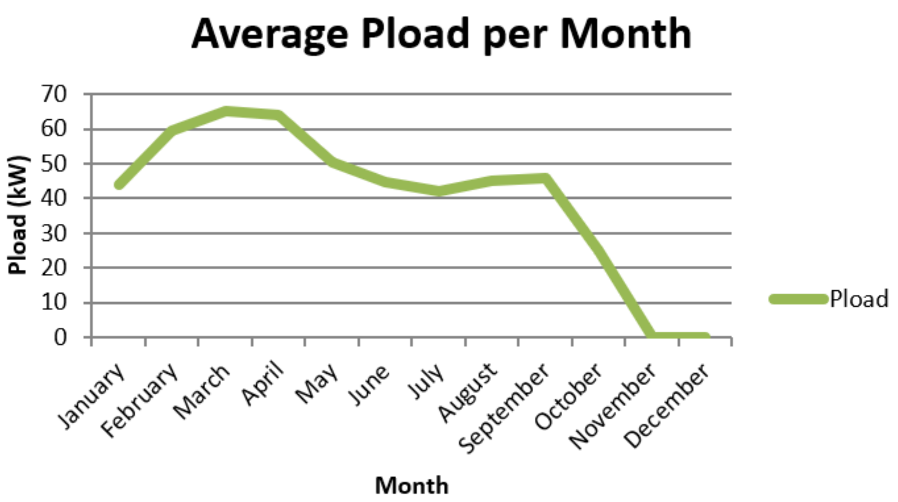

Figure 6:Electric Load

Validation of E_load

To verify the accuracy and physical consistency of the computed electrical load (E_load), a comparative time-series analysis was conducted using three key variables: thermal production, electricity consumption, and E_load. These are illustrated in the first graph.

Given that the dataset for electricity consumption (E_consumption) includes both the end-user electrical demand and the electricity supplied to the electric boilers, it can be decomposed as:

$$E\_consumption = E\_boiler + E\_load$$

Accordingly, fluctuations in thermal production—which directly influence the operation of the electric boiler—are expected to inversely affect E_load.

The plotted results confirm that E_consumption remains relatively stable over time, consistent with actual operating data. In contrast, thermal production displays a distinct cyclic pattern, reflecting the on–off control logic of the diesel generators responsible for heat supply. During periods of reduced thermal production—when the generators are not fully meeting the thermal demand—a corresponding decrease in E_load is observed. This behavior is consistent with the system dynamics: as more electrical energy is diverted to power the electric boilers, the amount available for other electrical loads decreases.

This inverse correlation validates that the derived E_load values accurately represent the residual electrical demand not allocated to thermal support.

The second graph further corroborates this relationship by incorporating additional variables: Q_boiler, thermal consumption, and Q_tank. It becomes evident that during intervals of insufficient thermal production, Q_boiler increases to compensate, and this increase directly translates into a reduction in E_load. Through this cross-variable consistency, the estimated values for E_boiler and consequently E_load are effectively validated.

This multi-level validation process reinforces the reliability of the methodology used to disaggregate the electricity consumption data. It ensures an accurate representation of both thermal and electrical subsystems within the simulation framework.

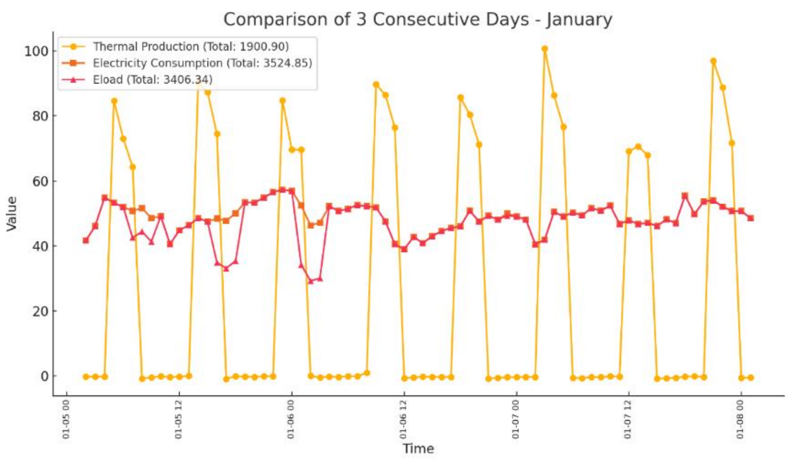

Figure 7:Validation of Eload_January

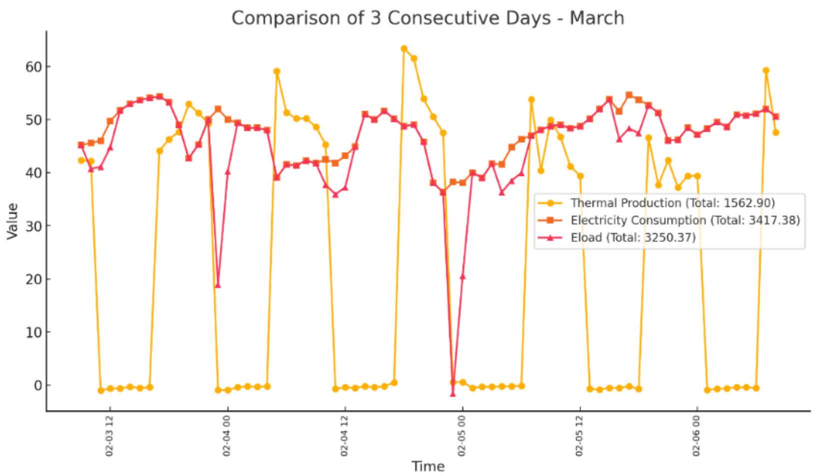

Figura 8: Validation of Eload_March

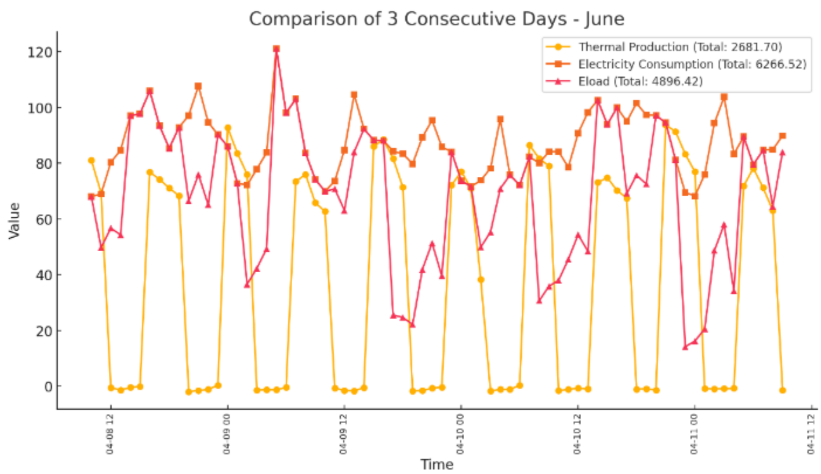

Figure 9:Validation of Eload_June

Thermal Balance Verification

As a further step in validating the reliability of the computed E_boiler—and, by extension, E_load—a focused analysis was conducted over a three-day period in February. This assessment examined the interaction among key thermal parameters, specifically:

- Q_tank (variation in thermal energy stored in the tanks)
- Thermal consumption
- Thermal production
- Q_boiler (thermal energy supplied by the electric boilers)

The plotted data indicate that thermal production (represented by the pink line) follows a cyclical trend, corresponding to the intermittent operation of the diesel generators. During periods when thermal production is insufficient to meet total thermal consumption, an increase in Q_boiler is observed. This confirms that electrical energy is being used to cover the thermal shortfall via the electric boilers.This dynamic is also evident in the Q_tank curve: when thermal production exceeds consumption, energy is stored in the tanks (Q_tank > 0); conversely, when there is a deficit (Q_tank < 0), the system compensates by drawing energy from the thermal storage tanks.

The consistency across these variables validates the thermal balance equation:

Q_boiler + Q_production + Q_tank = Q_consumption

This agreement, derived from reprocessed experimental data, strengthens the validity of the computational model adopted for thermal energy analysis, and supports the accuracy of the indirect calculation method used for E_load.

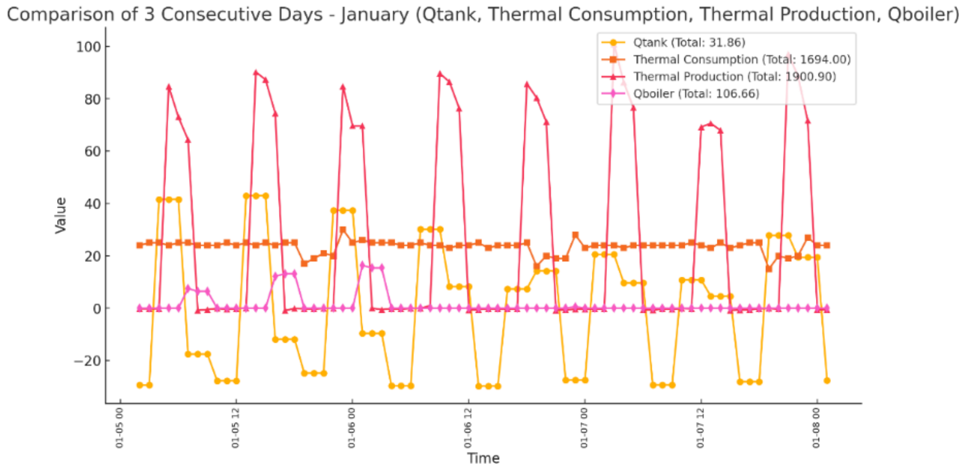

Figura 9:Validation_Eload_2_January

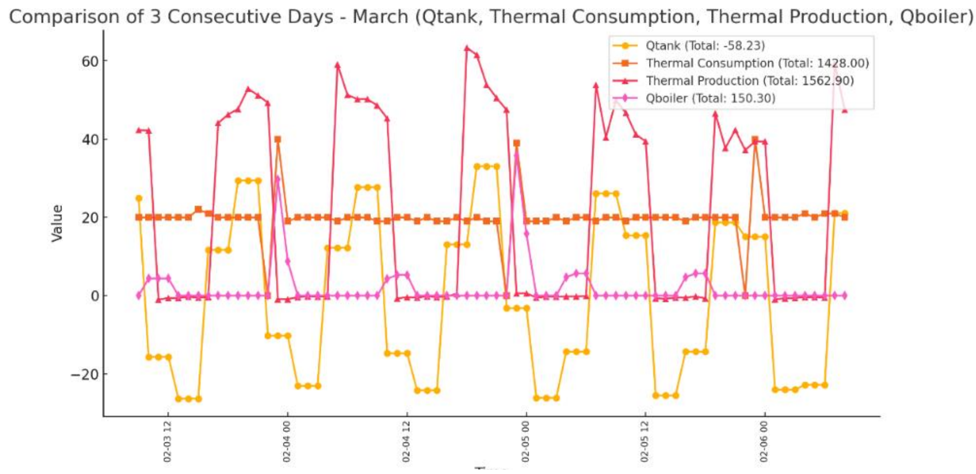

Figura 10:Validation_Eload_2_March

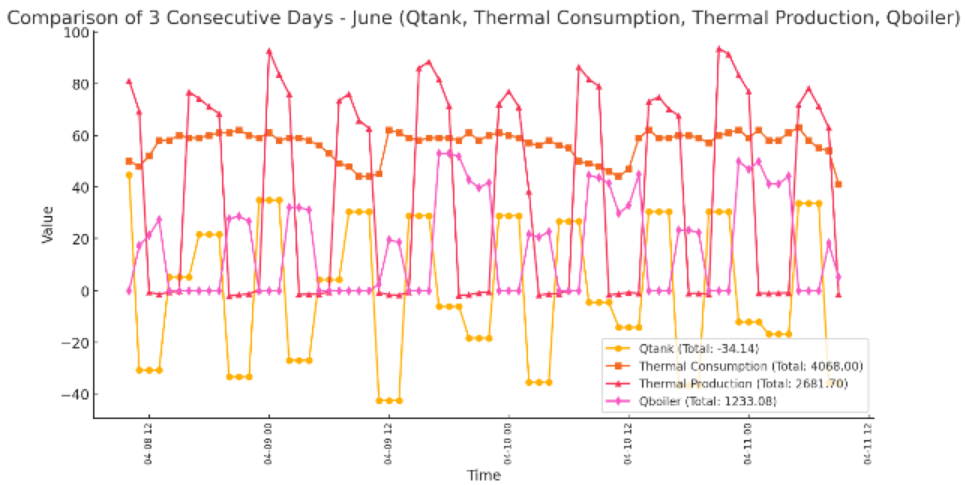

Figura 11:Validation_Eload_2_June pag 43

5. Modelling and Simulation Phase

5.1 Objectives and Scope of the Simulation

The simulation aims to assess the feasibility of a fully renewable, self-sufficient energy system at Isfjord Radio, using solar and wind as the sole primary sources, with hydrogen technologies (PEM electrolyzer, hydrogen storage, and PEM fuel cell) and batteries for energy balancing. The key objectives are:
• To determine whether the system can achieve energy self-sufficiency under different configurations.
• To identify the maximum hydrogen production rate, i.e., the peak production point over the simulation period.
• To derive practical and economic considerations, such as:
   - The required capacity and number of PEM electrolyzer and fuel cell units.
   - The volume and pressure of hydrogen storage required at peak.
   - Whether the identified system size is technically and economically viable.
   - If infeasible, the framework allows re-evaluating input assumptions, hydrogen storage types, or system configurations.

This simulation provides quantitative insight for future design decisions and supports strategic evaluation of different hydrogen pathways.

A simulation algorithm was developed in Python, incorporating time-series energy data and object-oriented control logic. The algorithm receives the following inputs:
• Hourly renewable energy availability (PV and wind power).
   - PV input is based on feed-in data from Solpark Isfjord Radio (200 kWp, 45° tilt, SINTEF dataset for 2023).
   - Wind input is derived from forecast-based calculations of 20 wind turbines (each 25 kWh), with Cp values averaged over 12 years (2012–2022), based on local meteorological stations.
• Hourly energy demand profiles, including:
   - Electrical consumption
   - Thermal consumption (space heating, hot water, and snow melting)

The thermal demand data were taken from 2022 (most complete dataset), while electric load was reconstructed by separating the electricity used for boilers from the total electricity consumption (details of this calculation were previously discussed).

• System component parameters:
   - PEM electrolyzer and fuel cell efficiency and capacity Pmin, Pmax etc.
   - Battery size, power min power max, SOC min max
   - Hydrogen tank limits

5.2 Logical Flow – Control Strategy

The system follows a central, rule-based control strategy encoded in a decision-making flowchart. The control logic evaluates energy flows at each time step to prioritize:

1. Direct RES use for loads. P_res is used in order to meet the load directly, then to charge the battery, and finally to power the electrolyzer for hydrogen production.

2. For thermal demand (Q_load), it is met using Q_storage, and if insufficient, the boiler is activated using energy from P_res, then from the battery, and finally from the fuel cell. Q_load may also be covered by Q_fc.

3. For electric load (P_load), RES is used first, followed by batteries, and finally by the fuel cell.

The system behavior is divided into two main branches: Electric Surplus and Electric Deficit.

➤ **Electric Surplus** (P_res > P_load)
• **CASE S1**: If RES > E_load and the remaining energy is enough to store (O_storage > Q_load), energy is used to charge the battery and operate the electrolyzer.
• **CASE S2**: If the remaining energy is lower than the required thermal energy (Q_boiler > O_storage - Q_load), the logic checks whether the storage can still meet the thermal load.
  o CASE S2.1: If so, battery and electrolyzer may be charged.
  o CASE S2.2: If not, RES energy is diverted to the boiler to meet thermal demand, and battery/electrolyzer remain unused.

➤ **Electric Deficit** (P_res < P_load)
• **CASE D1**: If storage can cover E_load deficit, energy is drawn from battery or fuel cell depending on the priority.
• **CASE D2**: If E_load > O_storage, thermal needs must be met as a priority.
  o If neither battery nor fuel cell can support Q_boiler, the system fails (not self-sufficient at that time step).
  o If fuel cell is sufficient but not battery, the fuel cell is activated.

Each decision path includes priority conditions, system limits (e.g., battery SoC, hydrogen tank capacity), and flow control based on logical comparisons.

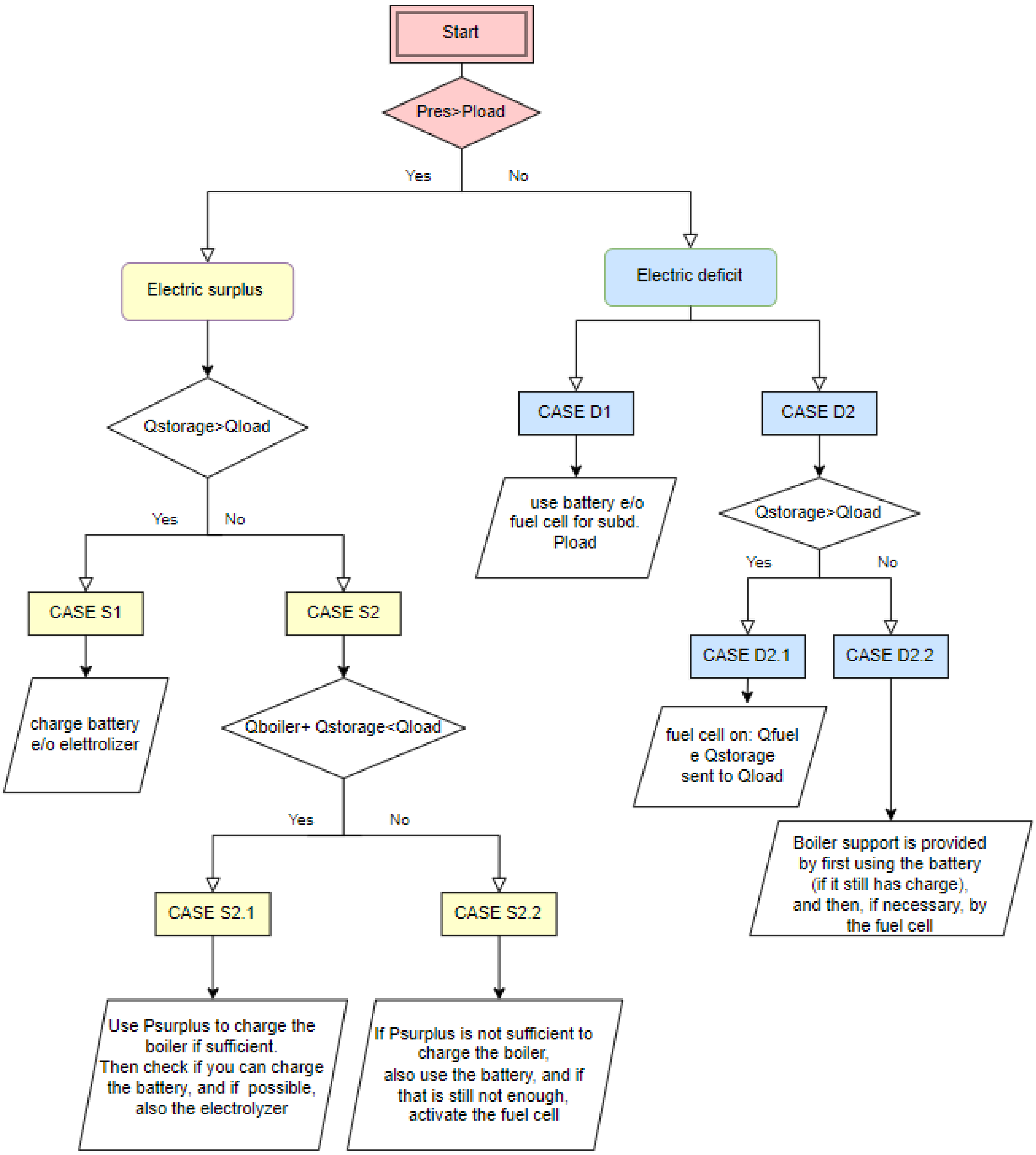

Figura 12:General_scheme_logic

The system behavior is divided into two main branches: Electric Surplus and Electric Deficit.

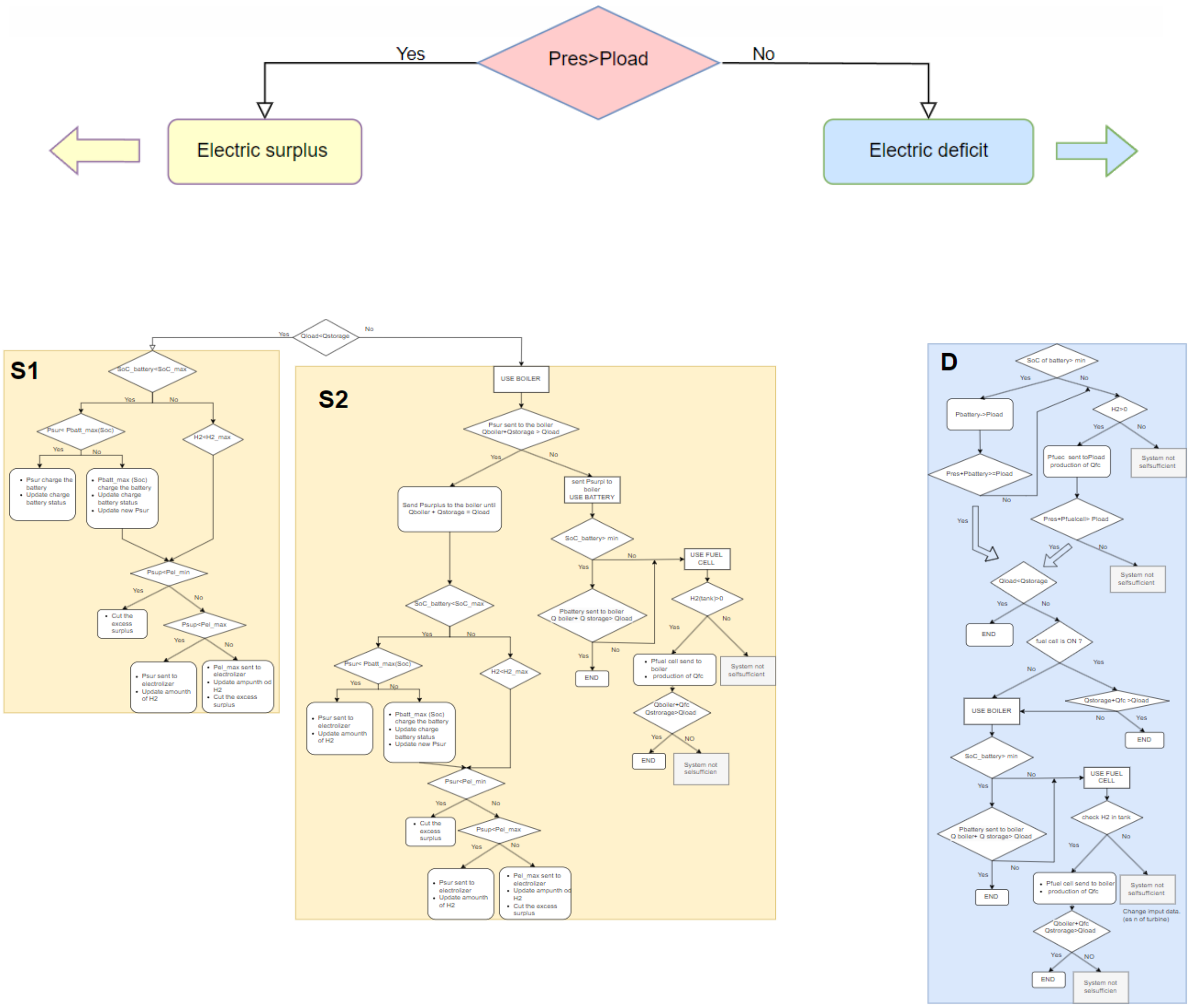

Figura 13:Complete_logic_scheme

5.2.1 Surplus Energy Case – S1

This operational state is triggered when the system experiences a surplus of renewable electricity, specifically when:

$$P_{RES} = P_{wind} + P_{solar} > P_{load}$$

and the thermal demand is already fully met by the available thermal storage:

$$Q_{storage} > Q_{load}$$

Under these conditions, the control algorithm evaluates how to allocate the surplus energy ($P_{surplus}$) in the following order of priority:

1. Battery Charging

The first check assesses whether the battery system is fully charged by comparing the current state of charge (SoC) to its maximum allowed level (SoC_{max}).

- If SoC < SoC_max, the battery is eligible for charging.
- If P_surplus ≥ P_batt,min, the battery is charged at a rate up to P_batt,max, and P_surplus is updated accordingly after the energy transfer.
- If the battery is already full or the available surplus power is insufficient for charging, the algorithm proceeds to the next step.

2. Hydrogen Production via Electrolysis

If the battery cannot absorb the surplus, the system checks whether the electrolyzer can be activated to produce hydrogen. This process involves two conditions:
- The hydrogen storage tank must not be full.
- The remaining surplus power must exceed the minimum operational threshold of the electrolyzer (P_el,min).

If both conditions are satisfied:
- The electrolyzer is activated and consumes power up to its maximum capacity (P_el,max), constrained by the remaining P_surplus.
- The amount of hydrogen stored is updated accordingly.

If P_surplus is below P_el,min, this excess energy is considered too small to be utilized efficiently and is therefore curtailed.

This hierarchical energy allocation strategy ensures that surplus renewable energy is optimally utilized to charge storage systems (batteries and hydrogen), while adhering to system constraints such as SoC limits and component operating ranges.

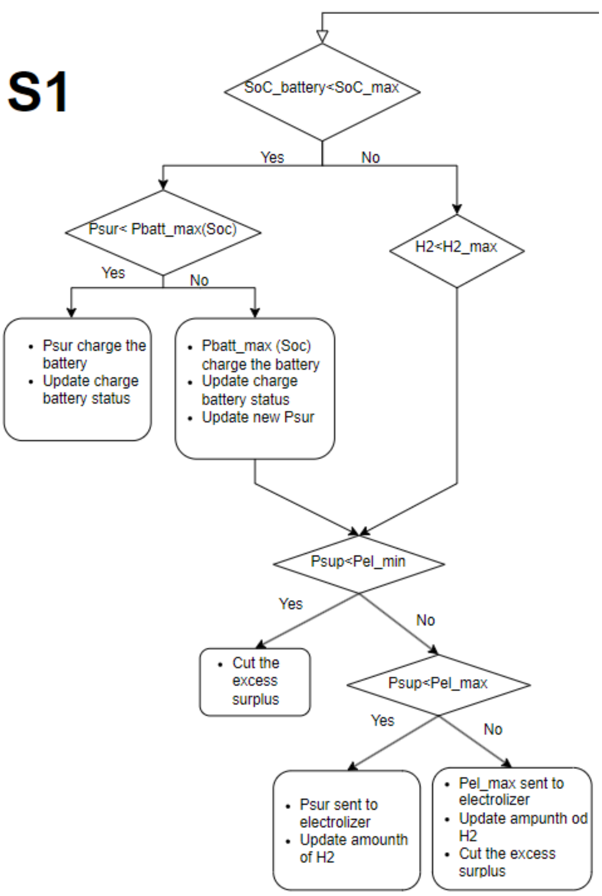

Figura 14:Logic_scheme_S1

5.2.2 Surplus Energy Case – S2

This operational case is triggered when the system has a surplus of renewable electricity:
P_RES = P_wind + P_solar > P_load
but the thermal storage alone is not sufficient to meet the thermal demand:
Q_storage < Q_load
In this situation, the system attempts to cover the thermal shortfall by activating the electric boiler. The control logic proceeds as follows:

1. Electric Boiler Activation

The surplus power (P_surplus) is directed to the electric boiler. The system checks whether the combined thermal output from the boiler and storage is sufficient:
Q_boiler + Q_storage ≥ Q_load
- If this condition is met, the boiler is supplied with P_surplus to meet the remaining thermal demand.
- If the condition is not satisfied, and even the full P_surplus is insufficient, the system stops diverting P_surplus to the boiler and proceeds to allocate it to other components (battery and electrolyzer), following the same logic as in Case S1.

2. Battery and Electrolyzer Allocation (if thermal demand can be met)

If thermal needs can be met (even marginally), the remaining surplus energy is evaluated for battery charging:
- If SoC < SoC_max and P_surplus ≥ P_batt,min, the battery is charged (up to P_batt,max), and P_surplus is updated.
- If battery charging is not possible or completed, and the hydrogen tank is not full, the electrolyzer is activated (if P_surplus ≥ P_el,min), consuming energy up to P_el_max.

3. If Thermal Demand Cannot Be Met with P_surplus Alone

When neither Q_boiler + Q_storage is sufficient to meet Q_load, even with full P_surplus directed to the boiler, the system activates auxiliary energy sources in the following order:
- Battery Discharge: If batteries are charged (SoC > SoC_min), they are discharged to supply additional power to the boiler.
- Fuel Cell Activation: If hydrogen is available in the storage tank, the PEM fuel cell is activated. The fuel cell provides:
  - Additional electrical energy to power the boiler.
  - Useful thermal energy (Q_FC) that directly contributes to covering Q_load.

4. Non-Self-Sufficiency Condition

If, after utilizing all available sources (thermal storage, boiler, batteries, and fuel cell), the system still fails to meet the thermal demand Q_load, the system is considered non-self-sufficient for that time step. This outcome signals the need to revisit the initial system configuration or input assumptions (e.g., storage capacity, RES availability, component sizing).

The schematic diagram of Case S2, as described above, is shown on the following page

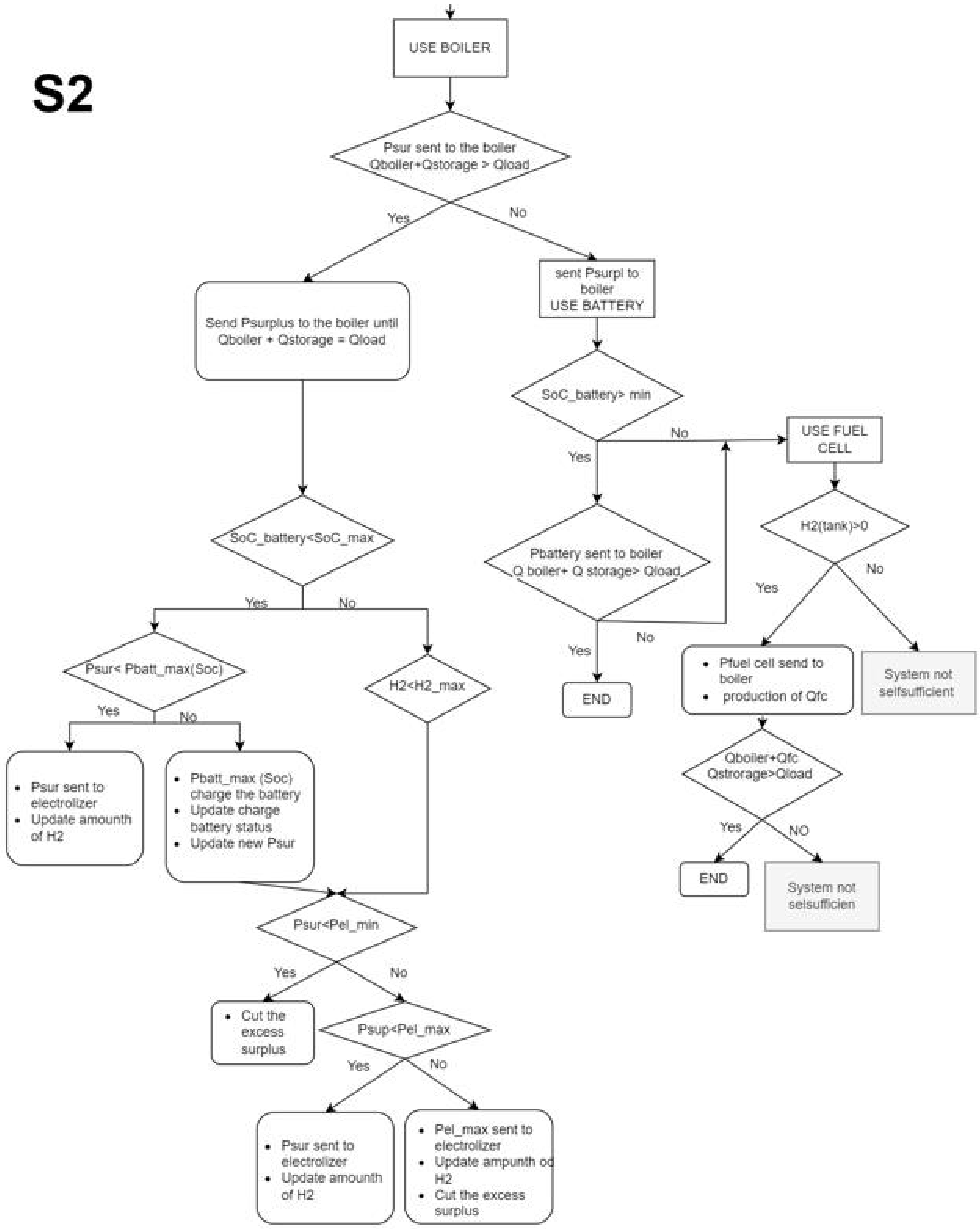

Figura 15: Logic_scheme_S2

5.2.3 Deficit Energy Case – D

This operational scenario is triggered when the available renewable energy is insufficient to meet the electrical load:

$$P\_RES = P\_wind + P\_solar < P\_load$$

In this case, the system follows a hierarchical logic to ensure energy demand is met while maintaining operational integrity. The process unfolds as follows:

1. Electrical Load Compensation

- Battery Discharge: The system first attempts to cover the P_load deficit using the battery storage.
  - If the battery is sufficiently charged (SoC > SoC_min), it is discharged up to its power limit to reduce or eliminate the deficit.
  - If the battery successfully meets the demand, the control logic proceeds to evaluate the thermal load.
  - If the battery is empty or its output is insufficient, the system attempts to activate the fuel cell.

- Fuel Cell Activation: The next step involves checking the hydrogen availability.
  - If hydrogen is present in the storage tank, the PEM fuel cell is activated to compensate for the remaining electrical deficit.
  - In addition to supplying electricity, the thermal energy produced by the fuel cell (Q_FC) is stored for potential use in the thermal subsystem.

- Non-Self-Sufficiency Condition:
  If the combined output of the battery and fuel cell is still insufficient to meet P_load, the system is deemed non-self-sufficient at that time step. This indicates a need to adjust the system design or input parameters.

2. Thermal Load Compensation

If P_load has been satisfied, the control logic proceeds to verify whether the thermal demand (Q_load) can be met.

- Thermal Storage Check:

  - If Q_storage ≥ Q_load, the demand is satisfied, and the system proceeds without further action.

- Combined Heat from Storage and Fuel Cell:

  - If thermal storage is insufficient and the fuel cell is already active, the system evaluates whether the sum of Q_storage and Q_FC can satisfy Q_load.

  - If this condition is met, the thermal demand is fulfilled.

- Boiler Activation via Battery:

  - If the above sources are still insufficient, and there is no residual renewable energy available, the boiler is activated using power from the battery (provided the battery still has available charge).
  - The boiler operates to produce the remaining required heat, and the system checks whether this action satisfies Q_load.

- Boiler Activation via Fuel Cell (Secondary):
  - If the battery is discharged or still insufficient, the system activates the fuel cell—if not already in use—to supply electricity to the boiler and use its waste heat directly for thermal demand.

  - Hydrogen storage is updated to reflect the usage.

- Final Failure Condition:
If, after exhausting all available sources (thermal storage, battery, and fuel cell), the system still fails to meet Q_load, the configuration is declared non-self-sufficient. This outcome signals the necessity of adjusting system assumptions, such as component sizing or energy availability.

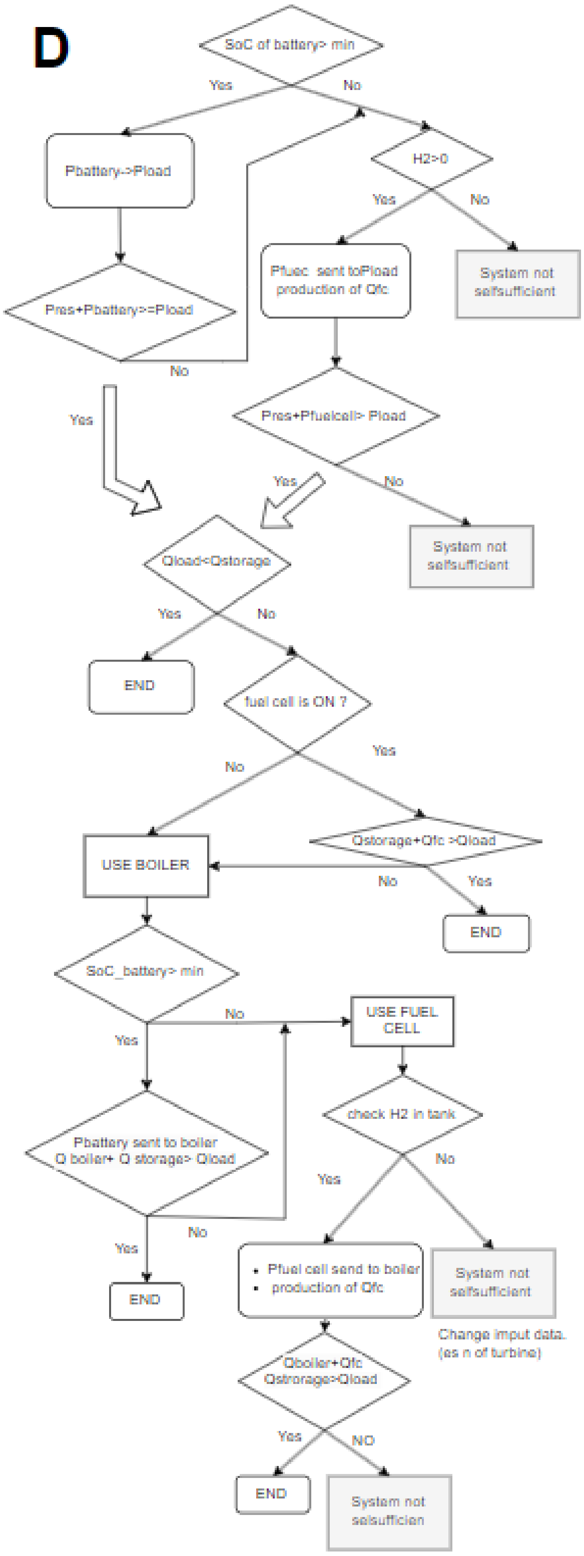

Figura 16:Logic_scheme_D

6.Input Parameters Simulation

This chapter presents the results obtained through numerical simulations performed using a Python-based energy model, described in detail in previous chapters. The simulations aim to evaluate the performance of various system configurations for a remote energy site (Isfjord Radio), considering a high share of renewable energy sources.

The configurations vary in terms of wind turbine size, battery capacity, electrolyzer and fuel cell power ratings, and hydrogen storage volume. Each scenario is assessed for its ability to meet electric (Pload) and thermal (Qload) demands, along with the behavior of energy storage components, namely battery state of charge (SoC) and hydrogen levels.
Below is a s
ummary table presenting the cases that were analyzed prior to proceeding with the final “solutions.”

Case	Turbines (kW)	Battery Storage (kWh)	Electrolyzer (kW)	Fuel Cell (kW)	H_2 Storage (kg)
0	1 × 25	3 × 76 = 228	10	2	15
0.1	1 × 25	3 × 76 = 228	10	2	50
1	1 × 25	23 × 76 = 1748	10	2	15
2	9.5 × 25 = 225	3 × 76 = 228	10	2	15
3	1 × 25	3 × 76 = 228	50	22	15
3_0.2	1 × 25	3 × 76 = 228	10	10	15
3_0.3	1 × 25	3 × 76 = 228	2	2	15
3_0.4	1 × 25	3 × 76 = 228	30	30	15
0_may	1 × 25	3 × 76 = 228	10	2	15
0.1_may	1 × 25	3 × 76 = 228	10	2	50
1_may	1 × 25	23 × 76 = 1748	10	2	15
2_may	9.5 × 25 = 225	3 × 76 = 228	10	2	15
3_may	1 × 25	3 × 76 = 228	50	22	15

Table4:Summary_imput_parameter'_case

Case 0

Case 0 represents the baseline configuration of the energy system at Isfjord Radio, composed of the following components:
Wind generation: one 25 kW wind turbine;
Electrical storage system: Three TESVOLT batteries, each with 76 kWh capacity, totaling 228 kWh;
Hydrogen system: One 10 kW PEM electrolyzer, a 2 kW fuel cell (initial assumptions), and a hydrogen tank with a maximum capacity of 15 kg.
Cleaned and pre-processed datasets were used for this simulation, with anomalies and outliers removed—particularly for the Pload variable, where negative or unrealistic values were set to zero. The simulation was initially started in January, with later simulations shifting the start date to observe the impact of starting the system when hydrogen and battery charging are more favorable.

Objectives
Provide an initial performance evaluation of the baseline configuration;
Analyze the behavior of storage technologies (battery and hydrogen);
Assess unmet demand and identify key bottlenecks.

Hydrogen Storage:

The hydrogen tank reaches its maximum capacity (15 kg) several times, indicating the electrolyzer is capable of operating effectively during surplus periods. However, the 2 kW fuel cell is severely undersized and is rarely activated, which limits the system's ability to use stored hydrogen. The visible end-of-year peak in hydrogen level and battery SoC should be disregarded, as Pload data is zero during that period and therefore not representative.
Sizing Justification for Electrolyzer and Fuel Cell:
The initial sizing reflects an approach where the system prioritizes hydrogen production during surplus energy periods rather than relying on H_2 for continuous load balancing.
The electrolyzer can accumulate hydrogen slowly over time from surplus renewable energy;
The fuel cell must meet instantaneous electrical loads and is often sized only for emergency or peak use due to higher cost and degradation concerns;
Fuel cells are more expensive and wear out faster, which discourages their continuous operation;
Efficient system design often limits the fuel cell size to ensure gradual and efficient use of hydrogen reserves.

Battery SoC (State of Charge):

Battery operation is dynamic during the summer, with frequent charge/discharge cycles. In contrast, batteries are nearly unused in winter. A brief full charge is recorded in October–November, followed by rapid depletion.

Unmet Demand:

- Qload (thermal): 4411 hours unmet;
- Pload (electric): 3970 hours unmet.
  These values reflect a critical level of system underperformance, especially in winter and spring months.

This simulation shows that the baseline configuration is not sufficient to ensure energy self-sufficiency for the site. Major weaknesses include:

- Inadequate renewable energy availability during cold seasons;
- Undersized fuel cell unable to support power loads;
- Insufficient battery and hydrogen storage capacity.

- Proposed Improvements
- Increase the number of wind turbines;
- Expand battery storage capacity;
- Enhance the electrolyzer and fuel cell power ratings;
- Increase the hydrogen storage volume.

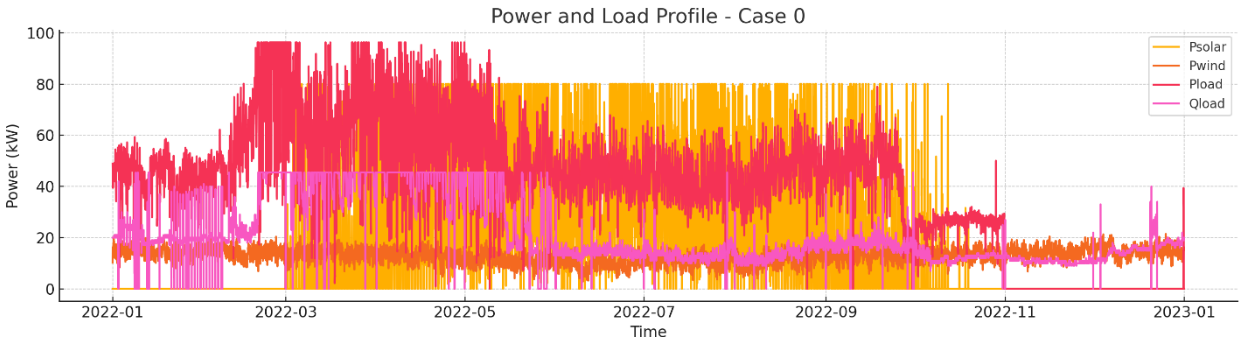

Figure 17: Pwind_Psolar_Pload_Qoal_CASE1

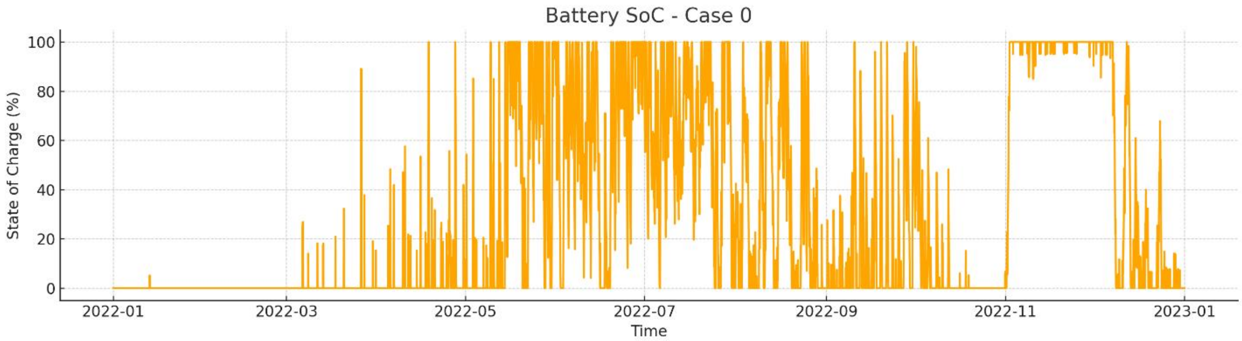

Figure 18:SoC_CASE1

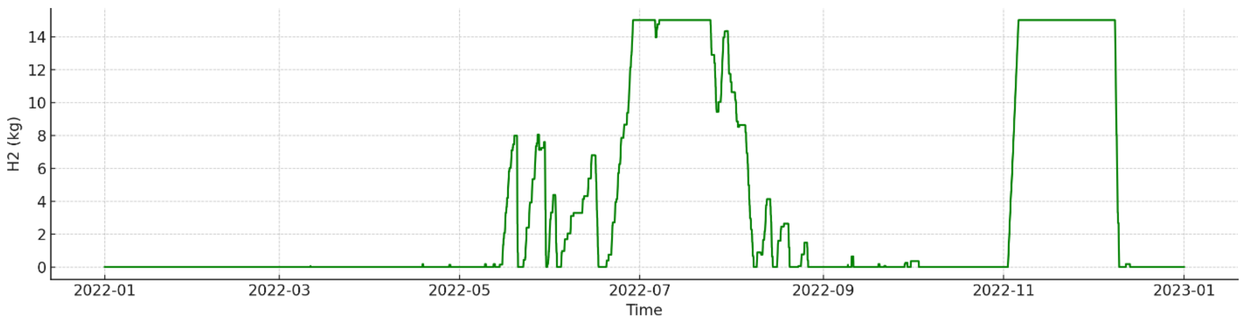

Figure 19:H2_CASE1

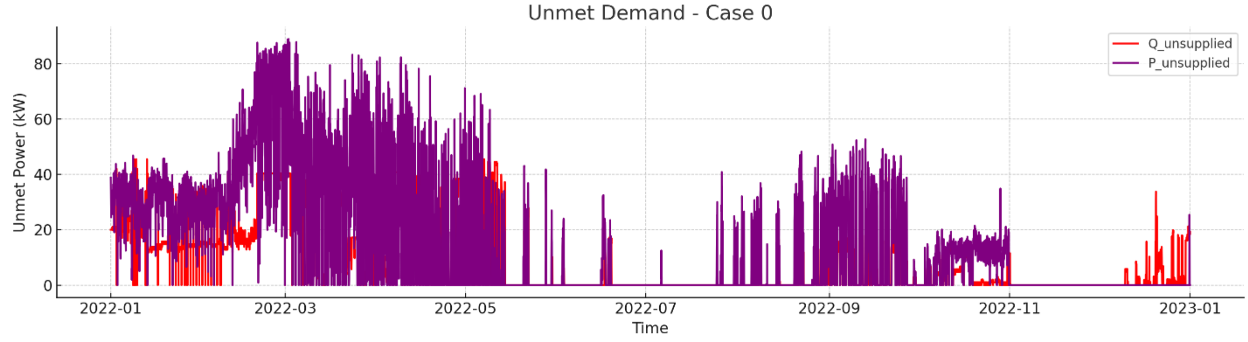

Figure 20 :Unmet Demand_CASE0

Case 0.1

In Case 0.1, the configuration is identical to Case 0, but with an increased hydrogen tank capacity (up to 50 kg) to assess whether more storage improves system performance without upgrading the electrolyzer or fuel cell.

Unmet Demand Comparison

• Qload (thermal): 4259 hours (reduced from 4411);
• Pload (electric): 3967 hours (almost unchanged).
The larger H_2 tank has negligible effect on overall system autonomy. The main bottleneck remains the 2 kW fuel cell, which cannot adequately convert stored hydrogen into usable electricity.

Hydrogen Storage

Hydrogen accumulates significantly during summer and autumn, reaching peaks of 50 kg. However, due to limited fuel cell capacity, much of the stored hydrogen remains underutilized.
As in Case 0, end-of-year data should be disregarded due to Pload = 0.

BatterySoC

Battery activity is slightly more intense than in Case 0, with more frequent cycles and brief autumn saturation. However, the system behavior remains suboptimal in non-summer months.

Extending hydrogen storage capacity alone does not yield significant benefits without simultaneous increases in fuel cell and electrolyzer power. The system still experiences high unmet demand, especially during winter, confirming that storage alone is not a viable solution.

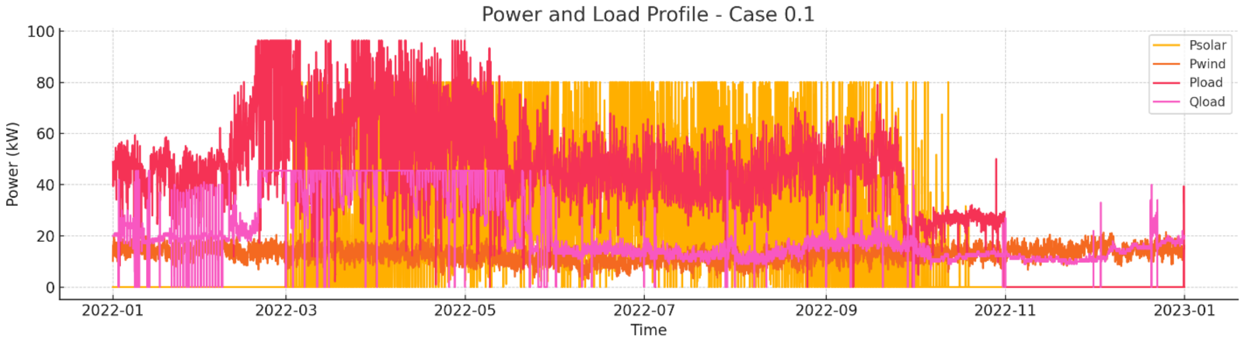

Figure21 :Pwind_Psolar_Pload_Qload_CASE0.1

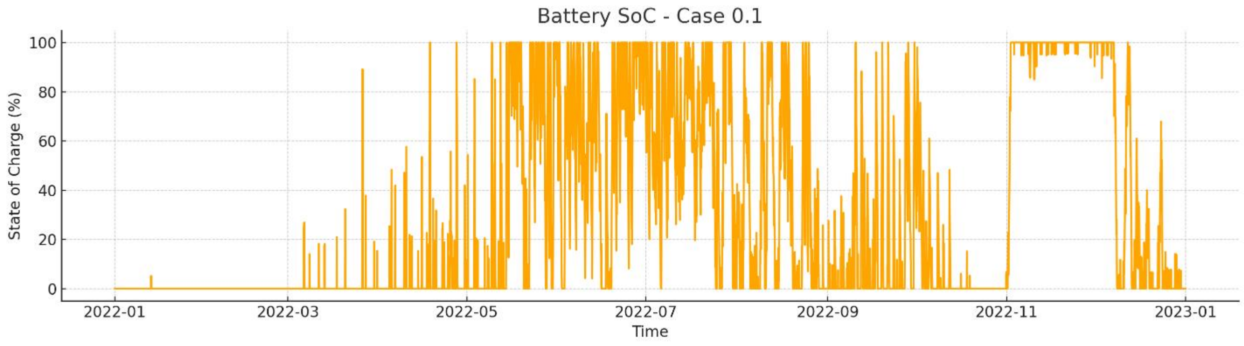

Figura 22: SoC_CASE0.1

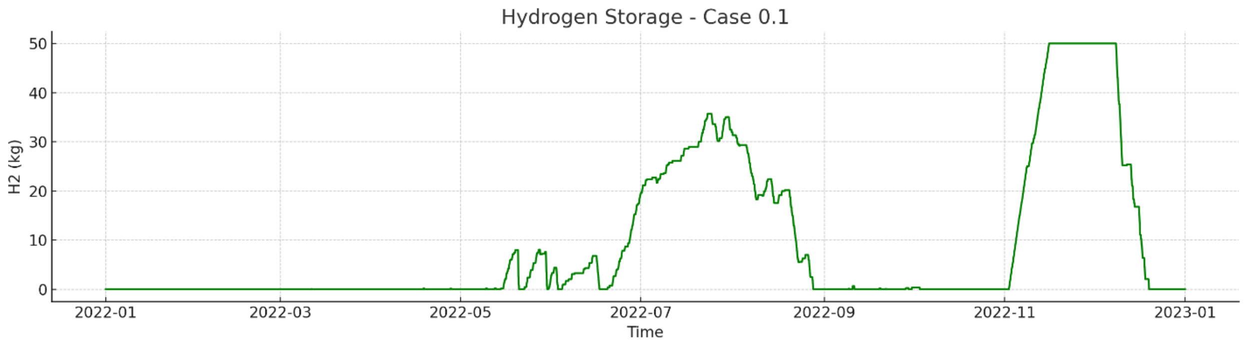

Figure 23:H2_CASE0.1

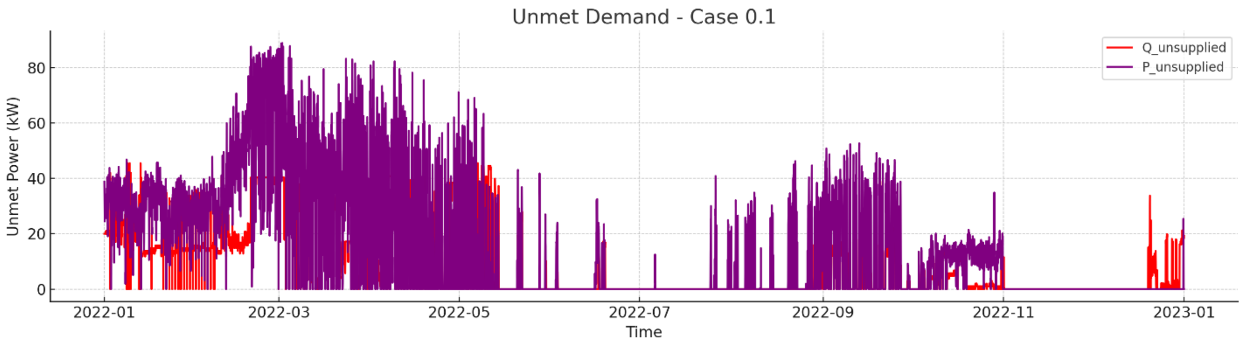

Figure 24: Unmet_Demand_CASE0.1

Case 1

In Case 1, battery capacity is significantly increased to evaluate whether the system can become self-sufficient using batteries alone. The selected configuration includes: 23 TESVOLT batteries of 76 kWh each, totaling 1,748 kWh.

Unmet Demand

• Despite the high battery capacity, the system still fails to meet the total load, particularly outside of the summer months.

• Qload and Pload remain unmet during winter and autumn.

Battery SoC

• Batteries only reach full charge during periods of significant surplus.
• SoC remains unstable, especially during colder months, and batteries often stay discharged.

Hydrogen Storage

• The system becomes highly "battery-centered," with hydrogen use being minimal or unnecessary.
• Hydrogen levels peak at 50 kg multiple times but are rarely utilized effectively due to unchanged fuel cell sizing.

This configuration offers notable advantages, primarily in terms of reliability and ease of control. Batteries are straightforward to manage, and their operation does not involve moving parts, which results in lower maintenance requirements and increased robustness during normal operation.

However, this approach also comes with significant drawbacks. The high number of batteries required—23 units in this case—translates into substantial capital investment (CAPEX), as well as a considerable physical and environmental footprint. Despite the large storage capacity, the system still fails to guarantee complete energy autonomy, particularly during periods of low renewable availability, such as the winter season.

Expanding battery storage alone—even at high capacities—is not a viable standalone solution. The system remains unable to cover critical loads year-round. Hydrogen-based solutions show better potential for long-term autonomy and cost-effective resilience, especially when properly integrated.

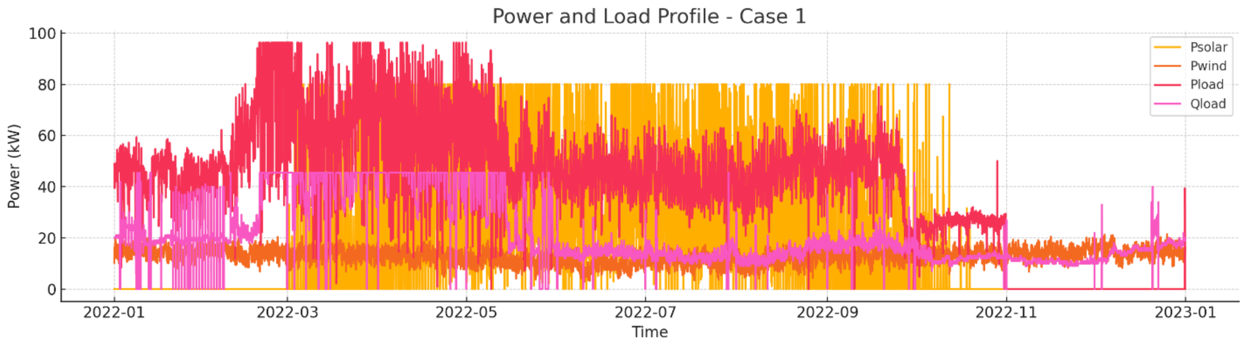

Figure 25:Pwind_Psolar_Pload_Qload_CASE1

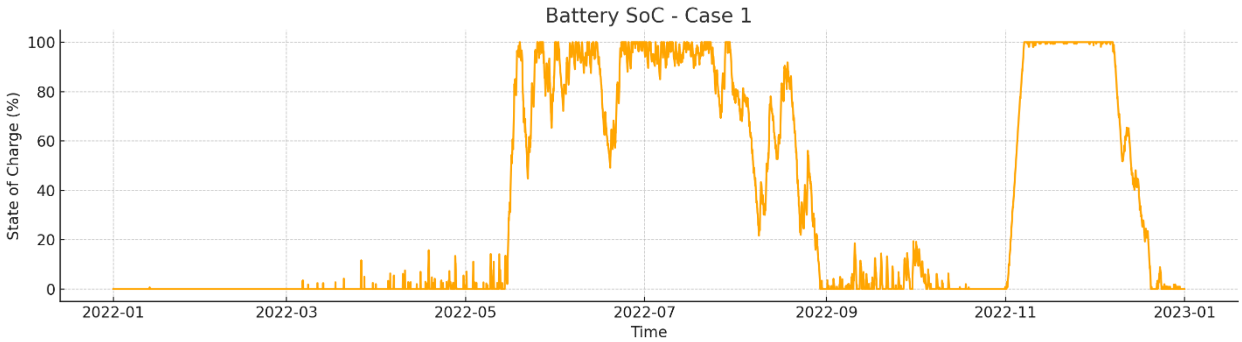

Figure 26:SoC_CASE1

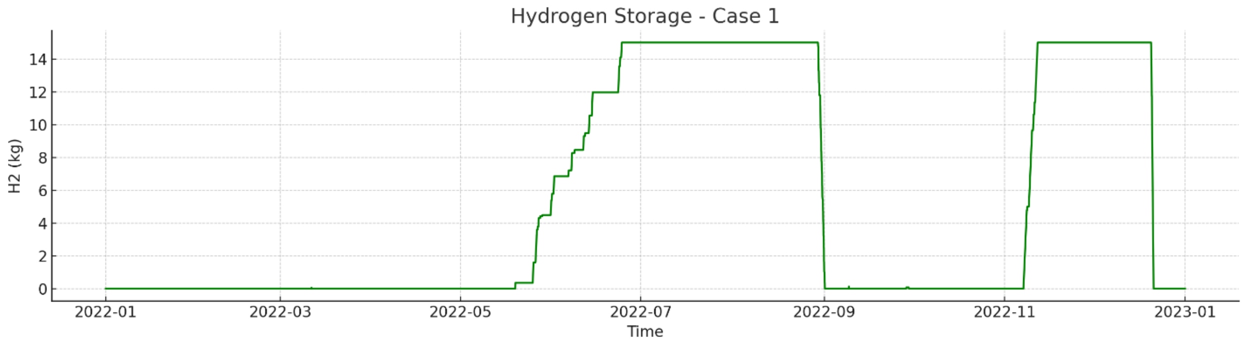

Figure 27:H2_CASE1

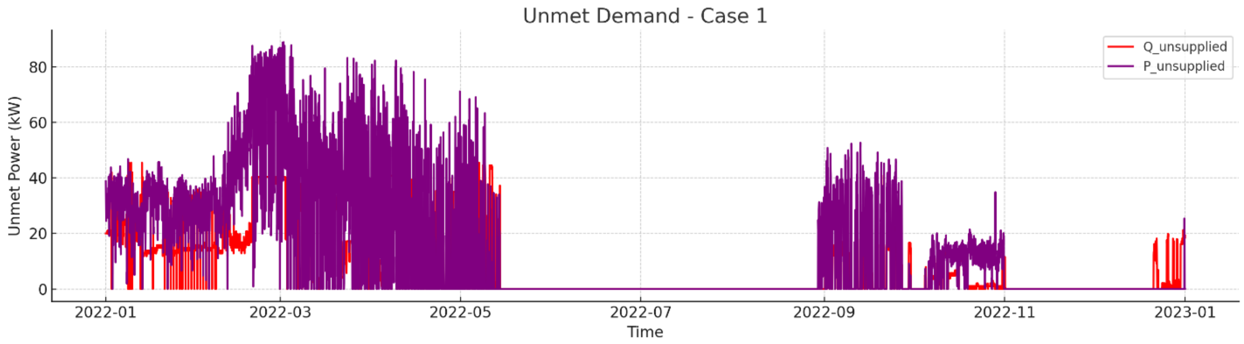

Figure 28:Unmet Demand_CASE1

Caso 2

In Case 2, the system focuses on increasing wind power generation as the primary means of achieving full energy autonomy. The selected configuration includes: 9.5 wind turbines rated at 25 kW each, totaling 225 kW installed capacity. (This would realistically be rounded up to 10 turbines in practical implementation.)

Unmet Demand

• Both Qload (thermal) and Pload (electric) demands are fully covered across the year.
• Only minor and isolated power shortages occur, mostly negligible.

Hydrogen Storage

• Hydrogen storage remains consistently full at 15 kg for most of the year.
• This indicates frequent production and minimal usage, consistent with an overabundant wind energy supply.
• The hydrogen system acts as a secondary buffer rather than a primary supply path.

Battery SoC

• Batteries remain nearly always charged, with the SoC frequently close to 100%.
• Minor fluctuations occur but do not impact system operation, due to constant wind availability.

• Batteries serve primarily to stabilize short-term fluctuations rather than provide seasonal storage.

Power and Load Profiles

• Wind power dominates the production profile, far exceeding both electrical and thermal load demands.

This wind-based configuration offers several compelling advantages. Most notably, it achieves full energy self-sufficiency using only renewable sources, with wind power alone proving sufficient to cover both electrical and thermal loads throughout the year. Once the turbines are installed, the system benefits from a significantly lower cost per kilowatt-hour, thanks to the low operational costs associated with wind energy. Furthermore, the surplus generation ensures that energy storage systems—both batteries and hydrogen—are only minimally relied upon. As a result, system operation becomes simpler and more predictable due to the steady and abundant wind input.
However, some key considerations must be acknowledged. The installation of 10 wind turbines requires a substantial amount of land, which, while not a constraint at Isfjord Radio due to the ample space available, might pose challenges elsewhere. In addition, the results of this case are highly dependent on the quality and representativeness of the wind data used in the simulation; inaccurate assumptions could lead to overestimating system performance. Lastly, the environmental and social implications of deploying a large number of wind turbines should be carefully assessed, particularly regarding their potential impact on bird migration and the local landscape.

Expanding wind generation proves to be a robust and cost-effective strategy for full system autonomy. With adequate spatial availability and proper environmental planning, this approach offers a sustainable long-term solution that minimizes reliance on expensive storage systems and achieves near-total load coverage across seasons.

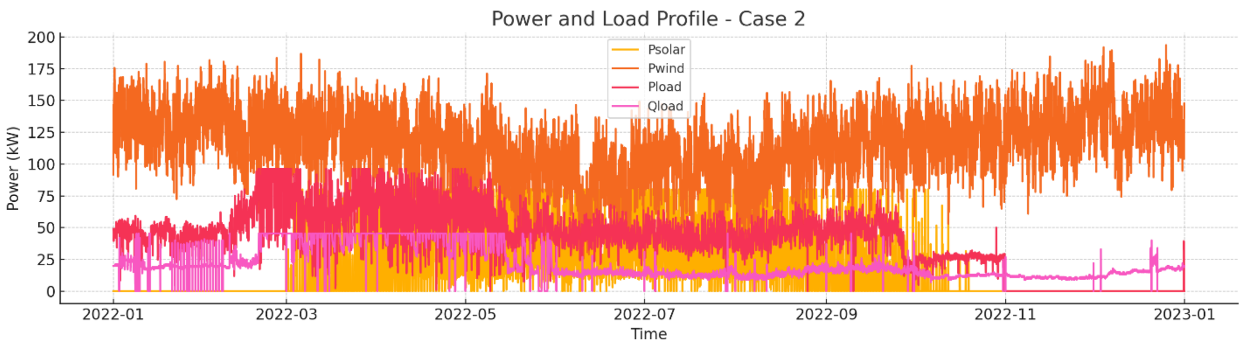

Figure 29:Psolar_Pwind_Pload_Qload_CASE2

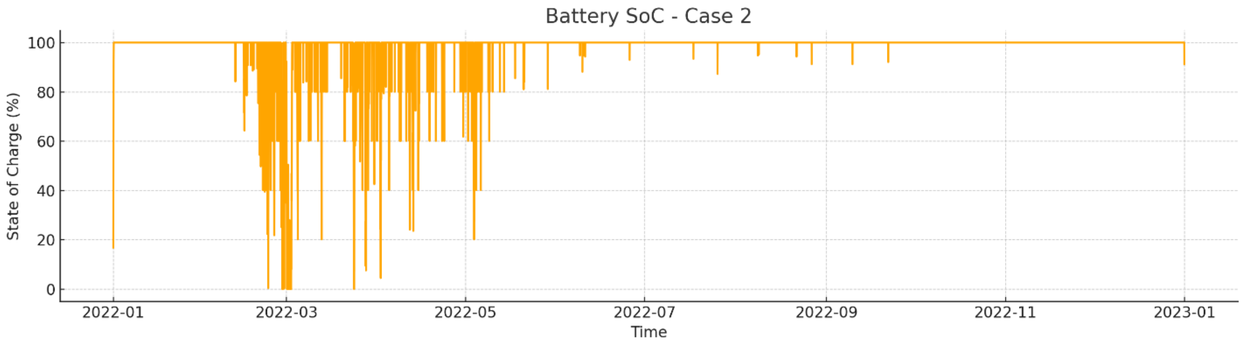

Figure 30: SoC_CASE2

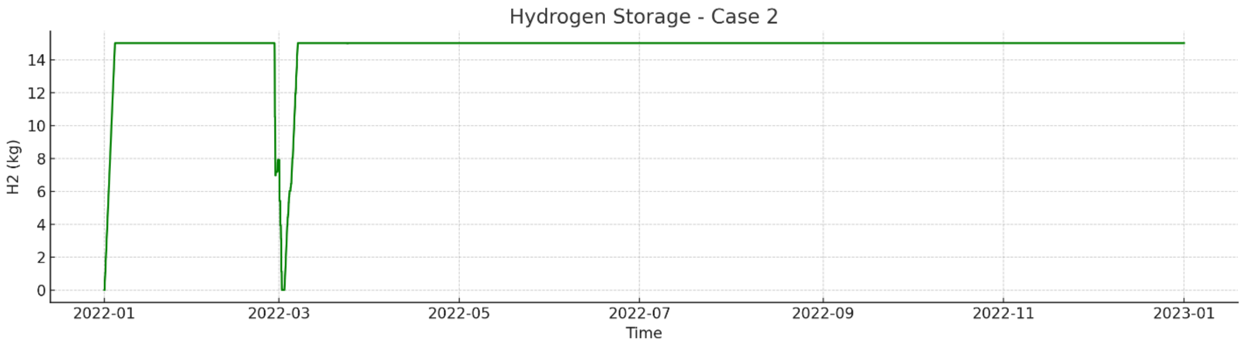

Figure 31:H2_CASE2

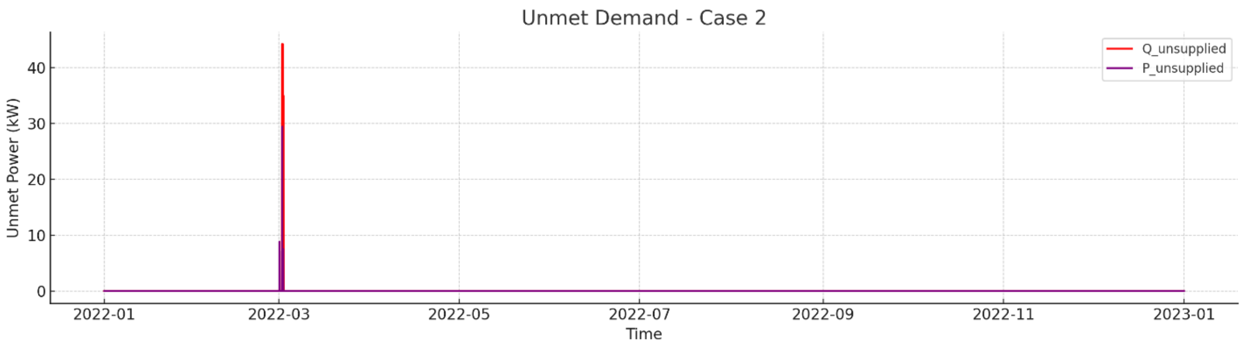

Figure 32:Unmet_Demand

Case 3

In Case 3, the hydrogen system is enhanced with a 50 kW PEM electrolyzer and a 22 kW fuel cell. This configuration is aimed at enabling strategic hydrogen use and better seasonal balancing. The hydrogen tank remains at 15 kg capacity.

• Significant upgrade in both electrolyzer and fuel cell capacity;
• System starts with an empty hydrogen tank in January, testing resilience from the most challenging period;
• Better synergy between electrical and chemical storage.

Hydrogen Storage

The system strategically uses surplus energy to produce hydrogen and later uses it to cover deficits. Hydrogen is effectively produced in the summer and utilized during winter and transition months. The tank frequently reaches full capacity, showing efficient surplus harvesting.

Battery SoC

Battery usage is well-balanced, with consistent cycling during surplus periods. The battery reaches full charge multiple times but is quickly discharged during high-demand periods, especially in winter.

Unmet Demand

- Thermal load (Qload): 4335 hours unmet;
- Electrical load (Pload): 3768 hours unmet.

While not completely eliminating unmet demand, the increased fuel cell power significantly improves resilience, especially during winter months.

Power and Load Profiles

Energy production and consumption show a better match, with solar and wind contributions utilized for both immediate load and hydrogen production. The system supports both electricity and heat supply through effective energy vector integration.

Scenario Assessment

From a technical perspective, this case proves the benefits of a well-balanced integration between batteries and hydrogen systems. Seasonal storage is efficiently managed by leveraging hydrogen during times of surplus and shortage. The fuel cell power is sufficient to meaningfully support loads, particularly during peak winter needs.

On the downside, the 22 kW fuel cell represents a considerable capital expense, and although there is notable improvement, full load autonomy remains out of reach. Nonetheless, this configuration is effective in reducing the scale of other infrastructure (e.g., turbines or battery banks).

Case 3 represents the most balanced solution in terms of cost, robustness, and ZEESA goals Provided it is obviously combined with Solution 2 (increase in turbines), thus enabling the system's full self-sufficiency. It demonstrates the strategic value of hydrogen as a seasonal storage medium in Arctic climates.

Key benefits include:

- Efficient hydrogen usage aligned with ZEESA priorities;
- Reduced need for bulky infrastructure;
- Combined heat and power generation increases overall efficiency;
- Higher social and environmental feasibility compared to more invasive alternatives.

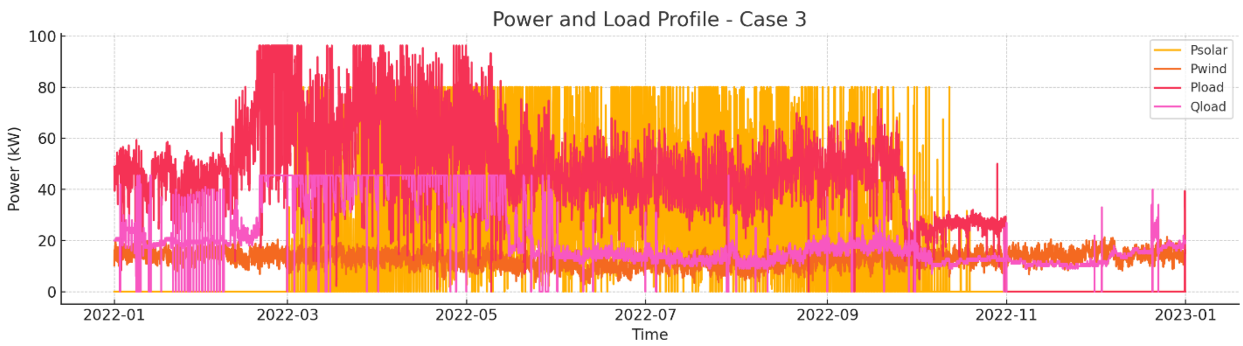

Figure 33:Pwind_Psolar_Pload_Qload_CASE3

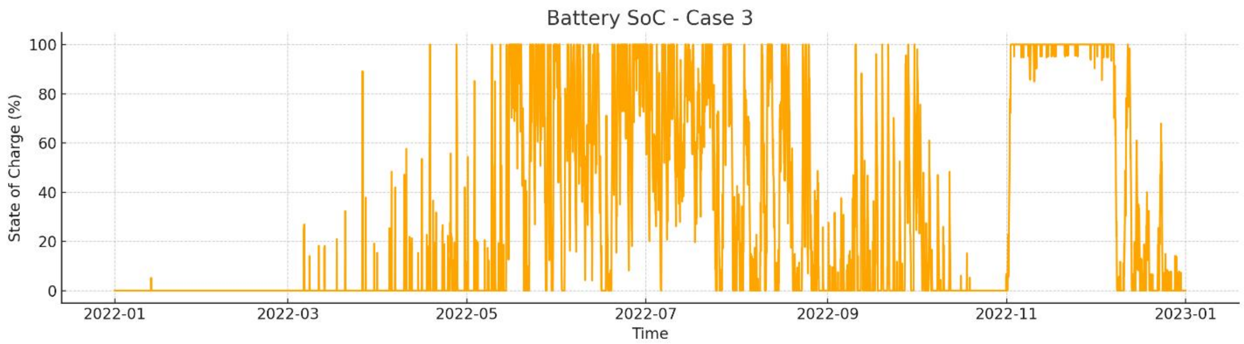

Figure 34:SoC_CASE3

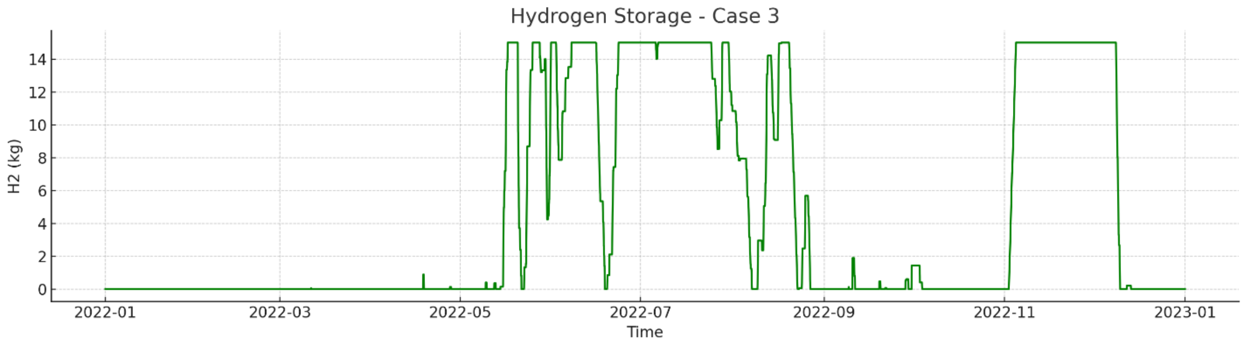

Figure 35:H2_CASE3

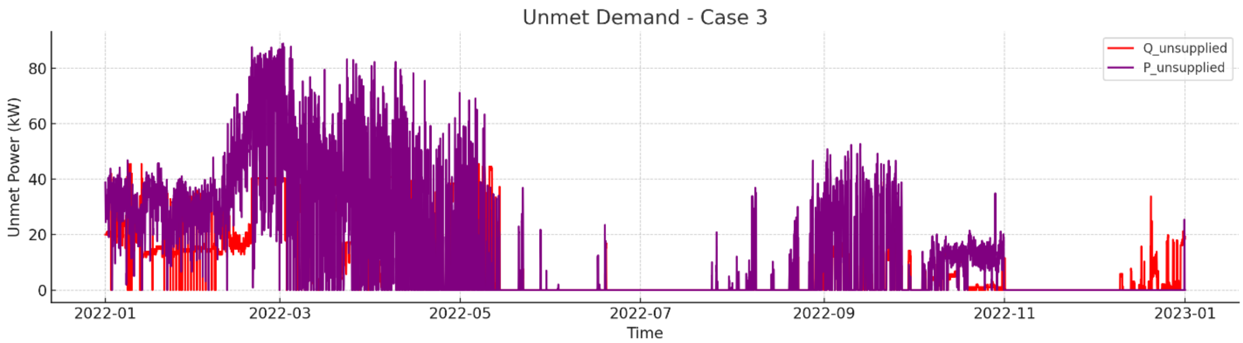

Figure 36:Unmet_Demand_CASE3

Case 3 _Evaluation of Matching Electrolyzer and Fuel Cell Power (Cases 0.2, 0.3, and 0.4)

In this set of tests, we explored the performance of the hydrogen system under three different configurations, all maintaining the same hydrogen storage volume but varying the installed power of the PEM electrolyzer and the fuel cell. Importantly, in these cases, the input and output hydrogen conversion capacities were matched: 10 kW, 2 kW, and 30 kW respectively.

The purpose of this comparison was to understand whether balancing the power capacities of these two components leads to significant improvements in load coverage, especially under the system's existing generation and storage constraints.

Case 0.3 (2 kW): This configuration unsurprisingly performs the worst. With only 2 kW of conversion capacity on both the electrolyzer and the fuel cell, the system struggles to meaningfully absorb or dispatch energy in hydrogen form. Hydrogen production is limited even when surplus energy is available, and fuel cell output is insufficient during deficit periods. This is reflected in the high number of unmet load hours: 4542 hours for thermal load and 3972 hours for electrical load.

Case 0.2 (10 kW): Here, we see a modest improvement. A 10 kW capacity on both devices enables the system to make better use of available renewable surpluses for hydrogen production and conversion. However, the tank size (still capped at 15 kg) and the seasonal profile of generation constrain the overall benefit. The hours of unmet demand are slightly reduced to 4418 for Qload and 3929 for Pload, suggesting some improvement in flexibility, but not enough to ensure reliability.

Case 0.4 (30 kW): This is the most powerful configuration tested. With 30 kW capacity for both the electrolyzer and the fuel cell, the system can process hydrogen much more quickly and responsively. As a result, it captures surplus energy more effectively and provides larger bursts of output when needed. Despite this, the number of unmet hours only slightly decreases to 4335 (thermal) and 3768 (electrical). This improvement, while notable, is limited by the small hydrogen tank, which fills quickly and depletes just as fast during high-demand periods, particularly in the winter.

These results indicate that merely increasing the power capacity of hydrogen components does help, but only to a certain extent. The most evident limitation across all cases is the restricted storage volume (15 kg). No matter how quickly hydrogen can be generated or used, the system lacks the buffering capability to bridge long periods of low renewable generation.

Another key takeaway is that matching the power capacity of the electrolyzer and fuel cell does not inherently lead to optimal system performance, Case 3 showed that an asymmetric configuration (e.g., PEMEL = 50 kW, FC = 22 kW) could lead to better results due to more strategic resource management.

While symmetry in hydrogen system design might simplify engineering and operation, it is not necessarily the most effective strategy for this Arctic application. Greater benefits are observed when hydrogen system sizing is adapted to the seasonal availability of renewables and the dynamic load profile. Ultimately, further gains in performance would require increased storage capacity and/or generation, rather than just enhancing conversion power.

Caso	Qload unmet [h]	Pload unmet[h]
0.2 (10 kW)	4418	3929
0.3 (2 kW)	4542	3972
0.4 (30 kW)	4335	3768
3	4335	3768

Tabella 5::Unmet_Demand_CASE3/0.2/0.3/0.4

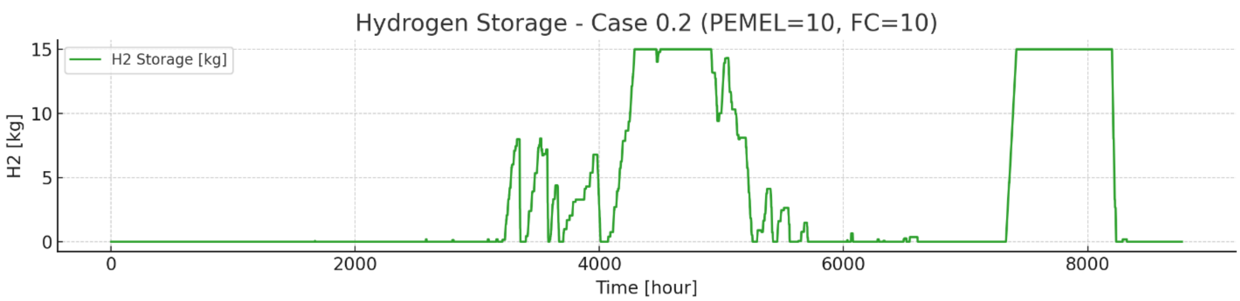

Figure 37:H2_CASE0.2

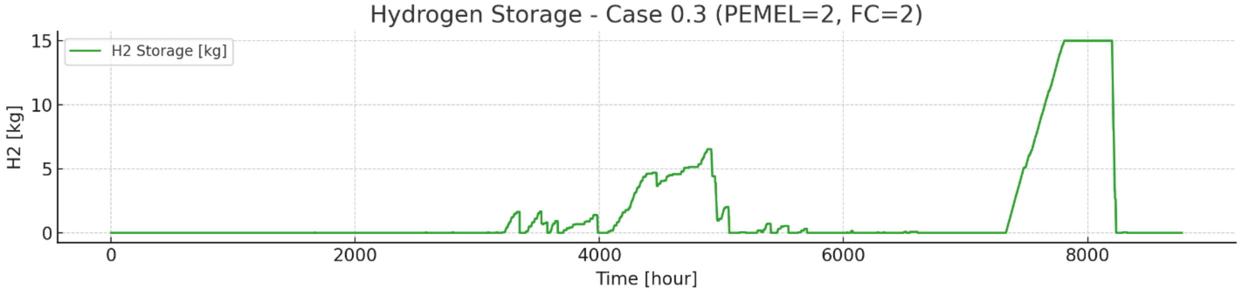

Figure 38:H2_CASE0.3

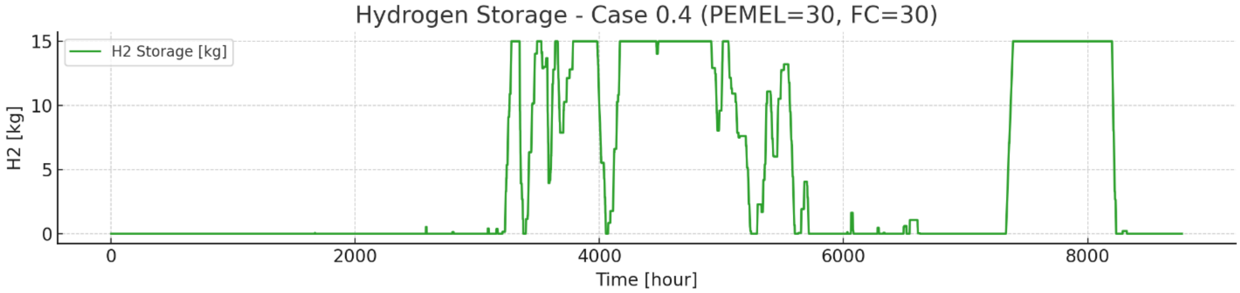

Figura 39:H2_CASE0.4

Case 0_May

To better evaluate seasonal behavior and storage dynamics, the simulation was repeated starting from May (instead of January), covering a full year. The intent is to observe how initializing the system in a period of high renewable availability and low thermal demand can enhance system resilience during the subsequent winter. Below is the case-by-case analysis.
With limited wind capacity and minimal storage, the system starts favorably in summer but struggles significantly during the winter period. From the graphs, it is evident that both battery SoC and hydrogen tank reach full capacity during summer, but they are rapidly depleted in the fall and early winter.

The hydrogen storage peaks twice, while SoC cycles frequently in the first half of the simulation. Unmet loads increase sharply around hour 6000, confirming that initial reserves are insufficient for long-term autonomy.

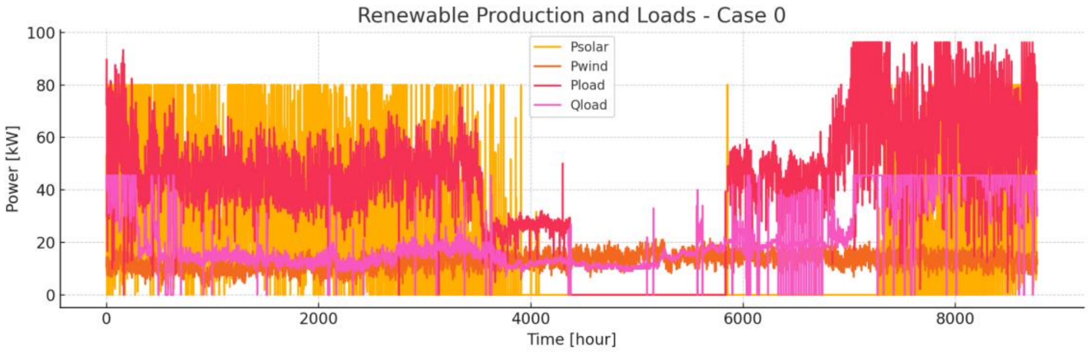

Figure 40:Pwind_Psolar_Pload_Qload_CASE0_MAY

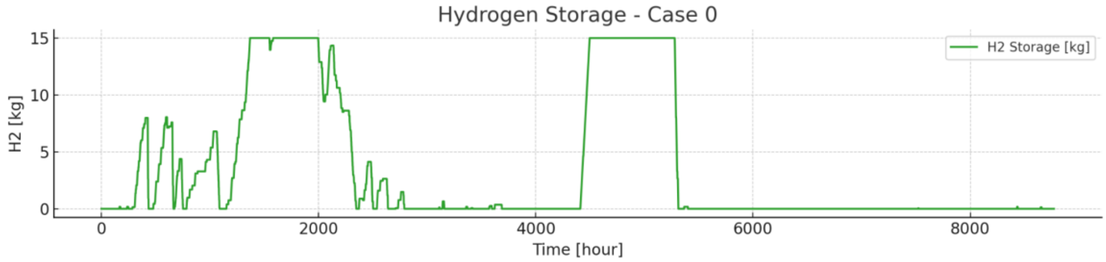

Figure 41:H2_CASE0_MAY

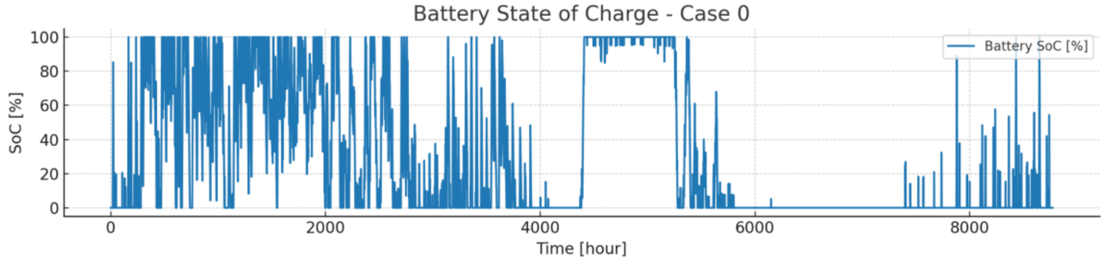

Figure 42:SoC_CASE0_MAY

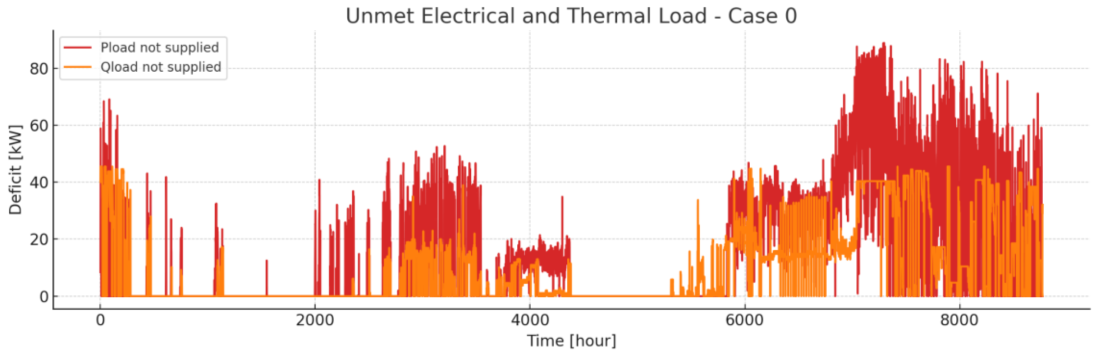

Figure 43:Unmet_Demand_CASE0_MAY

Case 0.1 – May

Increasing hydrogen tank capacity leads to more extensive summer storage. Hydrogen peaks above 125 kg before winter, which helps reduce unmet thermal hours compared to Case 0. However, due to the small fuel cell (2 kW), most of this stored hydrogen remains underutilized.

Battery behavior remains unchanged. Although thermal unmet load is reduced by ~250 hours, electrical deficit remains high due to the power bottleneck in conversion.

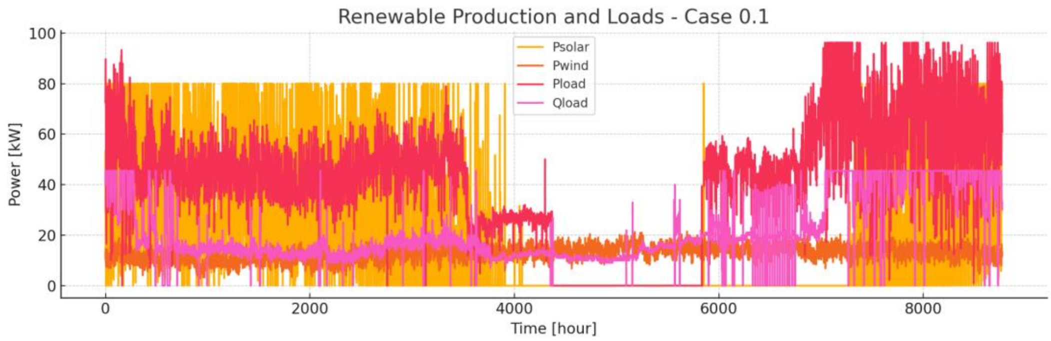

Figure 44:Pwind_Psolar_Pload_Qload_CASE0.1_MAY

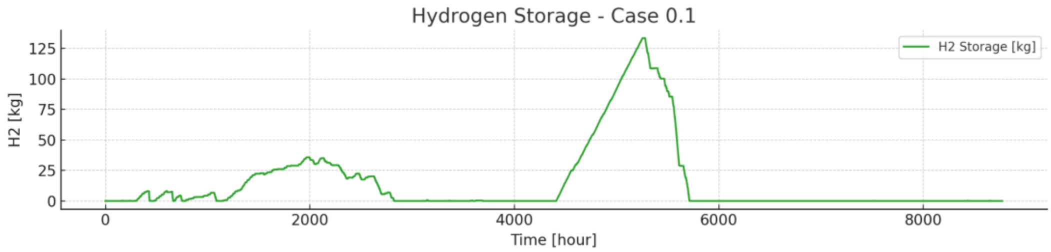

Figure 45:H2_CASE0.1_MAY

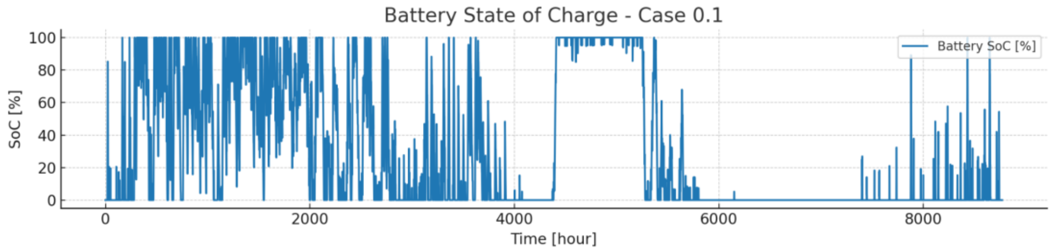

Figure 46:SoC_CASE0.1_MAY

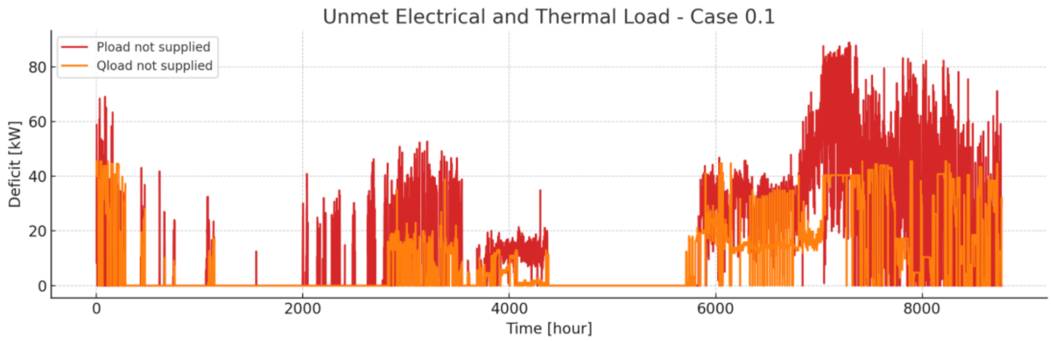

Figure 47:Unmet_Demand_CASE0.1_MAY

Case 1 – May

A total of 1748 kWh in battery storage allows for extensive daily balancing. From the load vs generation plot, it is clear that renewable input is consistently insufficient during winter months despite full summer charging. The battery reaches high SoC regularly in the first 4000 hours, but this advantage disappears later in the year.

Although electrical and thermal unmet loads decrease (compared to Case 0), winter resiliency is still limited. Hydrogen use is marginal due to unchanged 2 kW fuel cell.

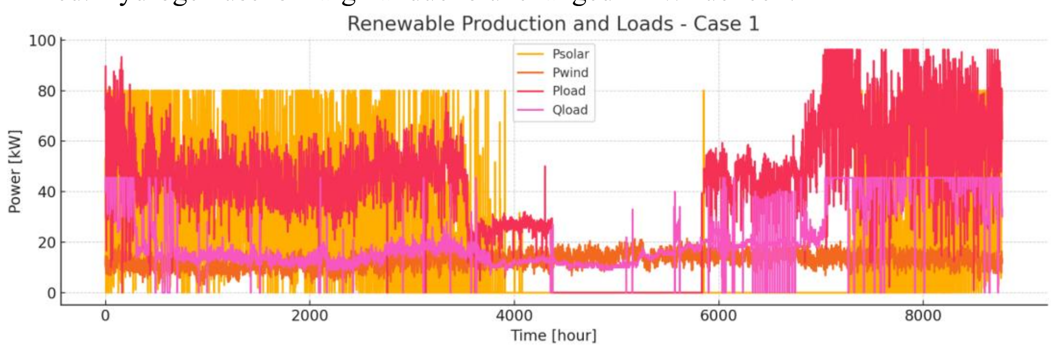

Figure 48:Pwind_Psolar_Pload_Qload_CASE1_MAY

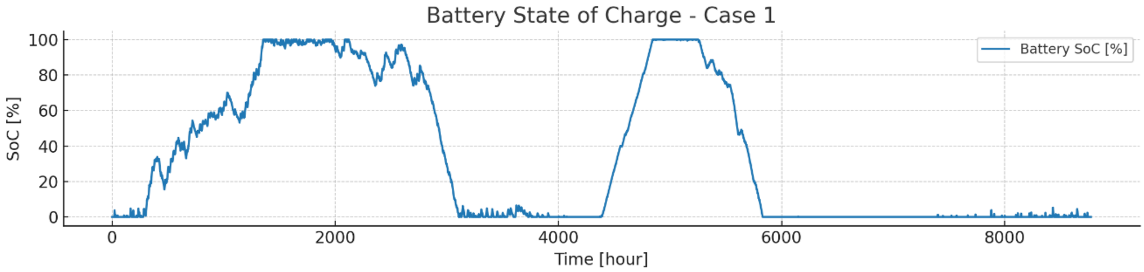

Figure 49 :SoC_CASE1_MAY

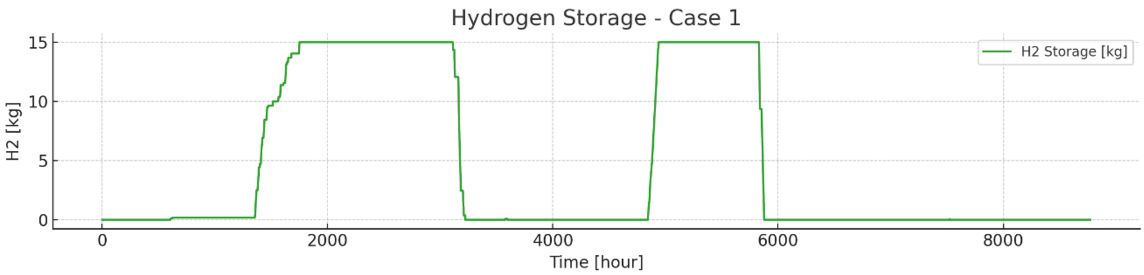

Figure 50:H2_CASE1_MAY

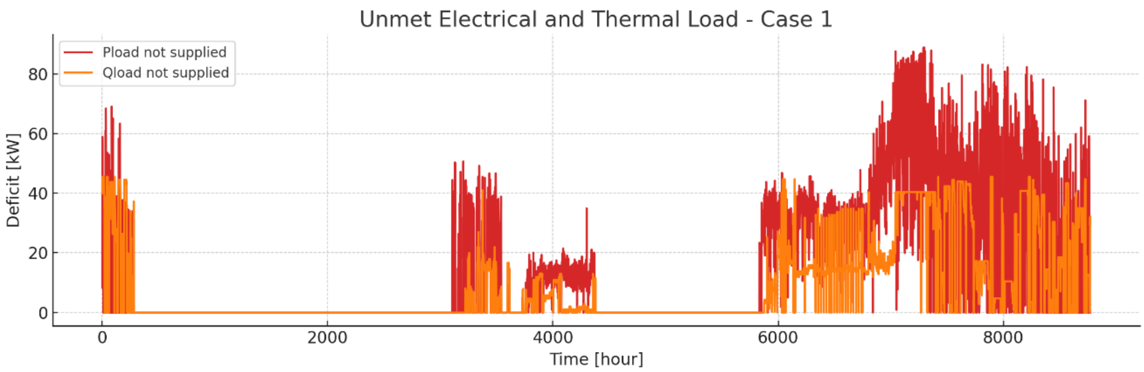

Figura 51:Unmet_Demand_CASE1_MAY

Case 2

Case 2 remains the most resilient configuration across all starting months. With 225 kW of installed wind power, the system consistently generates surplus renewable energy throughout the year. The result is near-zero unmet loads (only 3 hours thermal and 2 hours electrical).

Both battery and hydrogen storage are used marginally, indicating that real-time generation is sufficient to cover most of the demands. This confirms the robustness of a wind-dominant approach, particularly in Arctic sites where wind availability is high and stable. Case 3 – may

This case features a 50 kW PEM electrolyzer and a 22 kW fuel cell, maintaining 228 kWh of battery and 15 kg H_2 storage. Although the system has higher flexibility in using hydrogen during demand peaks, the wind generation is still not enough to support full autonomy. Hydrogen is frequently produced and consumed early in the simulation but runs out in winter.

Compared to Case 0 and 1, the larger fuel cell improves reactivity and reduces unmet load slightly. Still, the system suffers from renewable energy constraints, particularly evident beyond hour 6000.

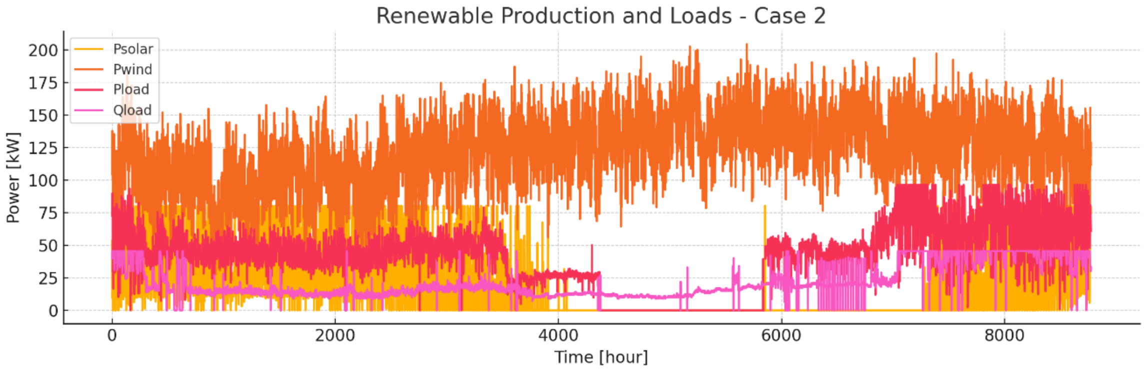

Figure 52: Pwind_Psolar_Pload_Qload_CASE2_MAY

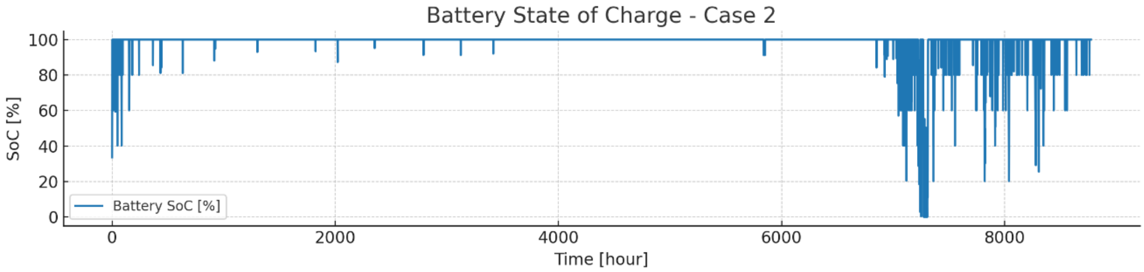

Figure 53: SoC_CASE2_MAY

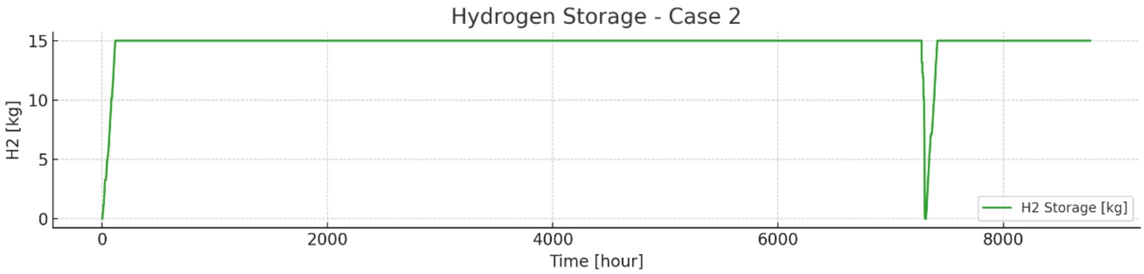

Figure 54:H2_CASE2_MAY

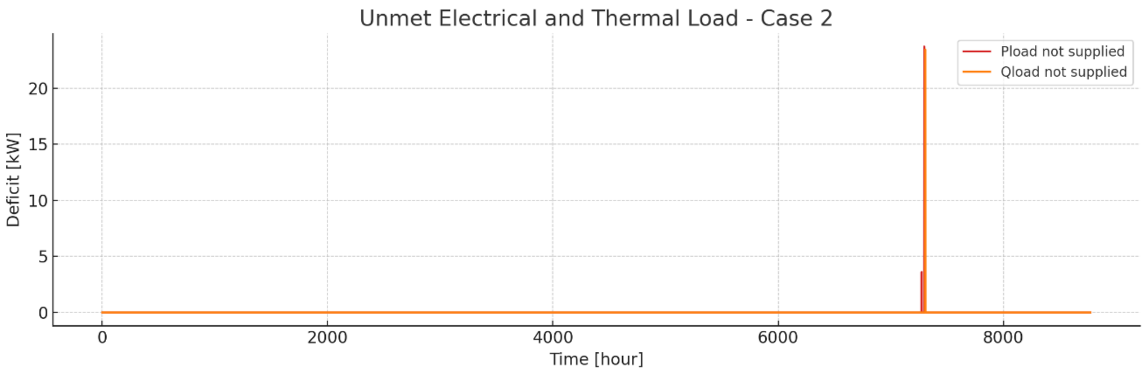

Figura 55: Unmet_Demand_CASE2

Case 3_may

In this configuration, the system includes a high-capacity 50 kW PEM electrolyzer and a 22 kW fuel cell, paired with moderate storage components (228 kWh battery and 15 kg hydrogen tank). Starting the simulation in May allows the system to enter the high-renewable season immediately, leading to early hydrogen production and battery charging.

This early advantage helps reduce unmet load slightly compared to the same case initialized in January. However, despite the increased flexibility and conversion power, the system remains constrained by limited renewable generation—especially wind—during the colder months. As a result, hydrogen reserves deplete rapidly in winter, and the unmet demand rises again beyond hour 6000.
While the improved hardware allows for more responsive and efficient use of surplus energy, full energy autonomy is still not achieved. This confirms that enhanced component sizing alone is not sufficient without a parallel increase in renewable input. Nevertheless, the earlier start contributes positively by shifting part of the energy burden to summer, effectively reducing stress on the system during the critical winter period.

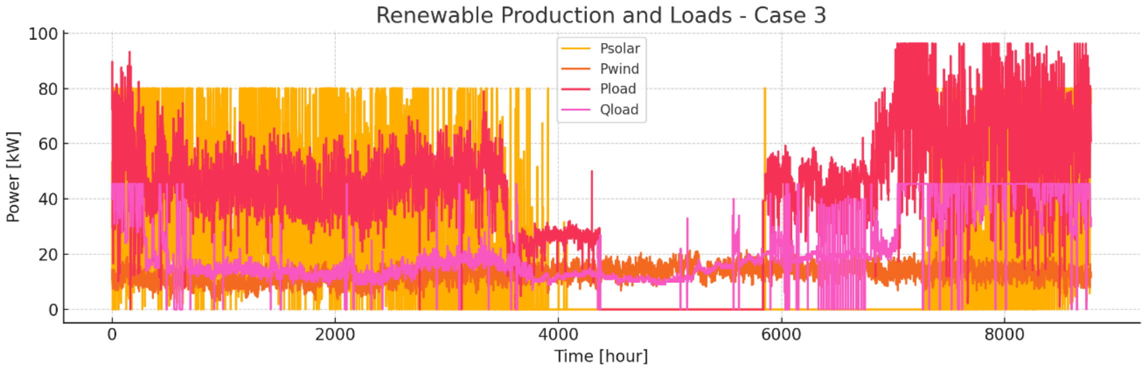

Figure 56: Pwind_Psolar_Pload_Qload_CASE3_MAY

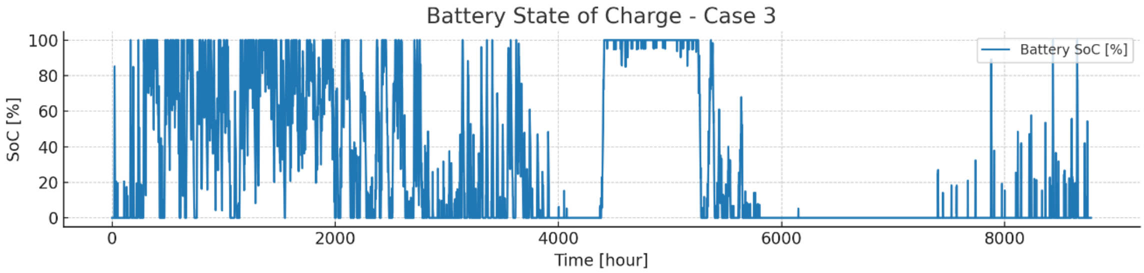

Figure 57: SoC_CASE3_MAY

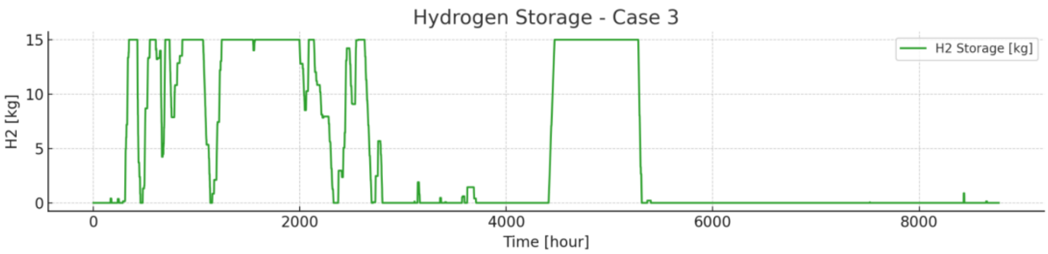

Figura 58:H2_CASE3_MAY

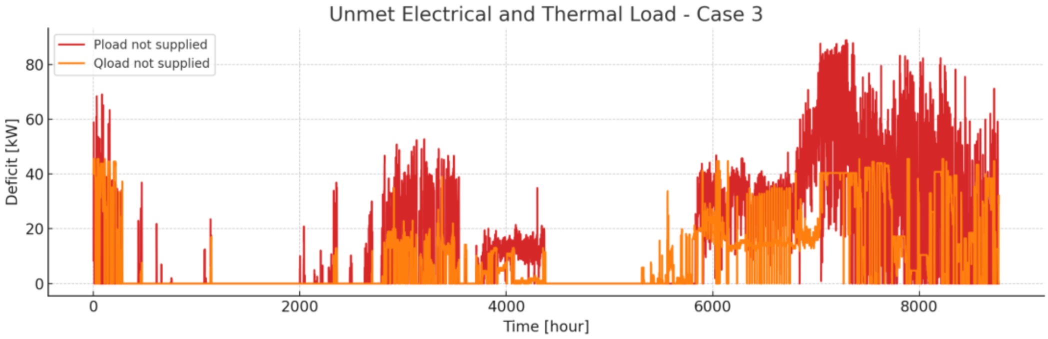

Figure 59: Unmet_Demand_CASE3_MAY pag 73

Sensitivity Analysis – Changing Start Month

This section explores how the initialization month of the simulation affects the performance of different system configurations. The start month influences the ability to pre-charge batteries and hydrogen tanks before winter, potentially reducing unmet demand later in the year.

Case	Start Month	Qload Not Supplied [h]	Pload Not Supplied [h]
Case 0	May	4411	3970
Case 0	June	4434	3980
Case 0	July	4423	3976
Case 0	August	4436	3989
Case 1	May	4071	3618
Case 1	June	3761	3432
Case 1	July	3766	3435
Case 1	August	3854	3568
Case 2	May	3	2
Case 2	June	3	2
Case 2	July	4	2
Case 2	August	4	2
Case 3	May	4313	3825
Case 3	June	4305	3825
Case 3	July	4305	3825
Case 3	August	4309	3831

Tabella 6: Unmet_Demand_Changing_Months

- Case 0: Small differences between months; performance is consistently poor due to lack of generation and storage.
- Case 1: Performance improves notably with earlier start months (May–June), thanks to battery pre-charging.
- Case 2: Near-perfect performance regardless of start month due to large wind capacity.
- Case 3: Results are nearly identical across months, indicating that system limitations are not strongly seasonal but structural.

The start month has a significant effect in medium-performing systems (e.g., Case 1), allowing energy reserves to be built up before winter. For under- or over-dimensioned systems, the effect is marginal.

6.1 Result

Case	Qload Not Supplied [h]	Pload Not Supplied [h]
0	4411	3970
0.1	4149	3967
1	3684	3420
2	3	2
3	4313	3825
3_0.2	4418	3929
3_0.3	4542	3972
3_0.4	4335	3768
0_may	4411	3970
0.1_may	4149	3967
1_may	3684	3420
2_may	3	2
3_may	4313	3825

Tabella 7: Unmet_Demand_Comparison different CASE

Starting the simulations in May offers a significant advantage in terms of system resilience. The early summer months, characterized by low thermal demand and high renewable energy availability, allow the system to accumulate energy in both the batteries and the hydrogen tank. This initial energy buffer helps mitigate the deficits typically encountered during the harsh winter season, when energy production is more limited and demand peaks.

It is worth noting that "starting in May" broadly refers to initiating system operation during the summer season (May, June, or July), as our simulations revealed no substantial differences between these months. Alternatively, this effect can be replicated by starting the system in winter with fully charged batteries and a full hydrogen tank—the final impact on system resilience is comparable.

However, the seasonal advantage alone is not sufficient unless supported by proper component sizing. Our findings indicate that:

Increasing battery capacity is possible but not necessary; in our analyses, the number of batteries was fixed at three units;

It is not essential for the electrolyzer and fuel cell to have symmetrical power ratings—indeed, asymmetric configurations proved to be effective;

The most critical condition for full energy autonomy is the presence of at least 10 wind turbines (25 kW each).

This finding confirms the strategic importance of Phase 3 of the ZEESA project, which foresees the installation of 10 to 20 turbines. The configurations analyzed in the next sections will therefore focus on systems with ten or more turbines, aligning with both the simulation results and the ongoing engineering development (led by the Benjiamo team).

Lastly, it must be emphasized that the wind power data used in the simulations are based on a mean capacity factor (Cp) calculated over the 2011–2021 period. While this average is representative, it may overestimate actual production, especially considering that Svalbard is an exceptionally windy location. For robust long-term planning, it is essential to include worst-case weather scenarios in the analysis—both for wind and solar inputs. Only by considering these conservative conditions can we accurately size the electrolyzer, the fuel cell, and the hydrogen storage system, ensuring uninterrupted system operation even in years with unfavorable climatic conditions.

7 Practical Solutions – System Design Under Stressed Conditions

The primary objective of this analysis phase is to identify design combinations that ensure complete system self-sufficiency even under unfavorable or extreme conditions. Rather than relying on historical averages, the simulation framework focuses on worst-case scenarios, which are essential for testing the system's robustness and resilience.

Definition of Stressed Scenarios

To replicate extreme operating conditions, the simulations include a combination of conservative assumptions related to renewable energy availability and energy demand. Specifically:

- Wind Power Reduction: A conservative reduction of the wind capacity factor (Cp) is applied, typically between –10% to –20% compared to the 2011–2022 historical average. Alternatively, the worst-performing year on record (e.g., 2018) may be used as a reference for a particularly poor wind year.

- Solar Energy Reduction: Global Horizontal Irradiance (GHI) or Plane of Array (POA) values are decreased by 10–20%, simulating conditions such as overcast skies or snow-covered panels—particularly relevant in polar or alpine regions during winter.

- Load Increase: Both electrical (P_{loa}d) and thermal (Q_{loa}d) loads are increased by 10–15% to represent potential future growth or harsher-than-usual winters. Alternatively, stressed demand profiles may be used, featuring persistent thermal peaks during the cold season.

These adjustments aim to stress-test the system against a combination of reduced generation and increased consumption, providing a robust assessment of its reliability.

Simulation Strategy

Simulations are initialized in January, assuming this represents the worst-case starting point due to low renewable availability and high thermal demand. Because of the computational intensity of this analysis, only a single stressed scenario is used, combining:

- –20% wind Cp

- –20% solar GHI/POA

- +15% load increase (P_{loa}d and Q_{loa}d)

Furthermore, the simulation follows a stepwise optimization process for identifying the minimum viable system configuration. The parameters are varied in the following sequence:

1. Hydrogen tank capacity

2. Fuel cell nominal power

3. Electrolyzer nominal power

Certain system parameters are held constant throughout, such as a fixed battery storage configuration (3 units of 76 kWh, totaling 228 kWh). Only hydrogen subsystem components (tank, fuel cell, electrolyzer) are dynamically adjusted.

Simulations revealed the following:

- With 10 or 11 wind turbines, the hydrogen tank size required to guarantee autonomy under stress conditions becomes excessively large and is therefore deemed impractical.
- Starting from 12 wind turbines, viable and efficient configurations emerge. Of these, configurations with 14 or 15 turbines perform particularly well and are selected for the economic analysis.

Below is a summary of simulation outcomes for different turbine counts:

12 turbine

PEMEL [kW]	Fuel Cell [kW]	H_2 Tank [kg]	P Deficit [kWh]	Q Deficit [kWh]
150.0	150.0	145.0	0.0	0.0
150.0	145.0	145.0	0.0	0.0
150.0	140.0	145.0	0.0	0.0
150.0	135.0	145.0	0.0	0.0
150.0	130.0	145.0	0.0	0.0
150.0	125.0	145.0	0.0	0.0
150.0	120.0	145.0	0.0	0.0
150.0	115.0	145.0	0.0	0.0
150.0	110.0	145.0	0.0	0.0
150.0	105.0	145.0	0.0	0.0
150.0	100.0	145.0	0.0	0.0
150.0	95.0	145.0	0.0	0.0
150.0	90.0	145.0	0.0	0.0
150.0	85.0	145.0	0.0	0.0
150.0	80.0	145.0	0.0	0.0
150.0	75.0	145.0	0.0	0.0
150.0	70.0	145.0	0.0	0.0
150.0	65.0	145.0	0.0	0.0
150.0	60.0	145.0	0.0	0.0
150.0	55.0	145.0	0.0	0.0
150.0	50.0	145.0	0.0	0.0
100.0	50.0	145.0	0.0	0.0
95.0	50.0	145.0	0.0	0.0
90.0	50.0	145.0	0.0	0.0
85.0	50.0	145.0	0.0	0.0
80.0	50.0	145.0	0.0	0.0
75.0	50.0	145.0	0.0	0.0
70.0	50.0	145.0	0.0	0.0
65.0	50.0	145.0	0.0	3.73

Tabella 8: Selfsufficient_configuration_12_turbine pag 76

With 12 turbines, the system remains fully autonomous down to 70 kW PEMEL and 50 kW FC. Further reductions begin to show minor deficits.

13 turbine

PEMEL [kW]	Fuel Cell [kW]	H_2 Tank [kg]	P Deficit [kWh]	Q Deficit [kWh]
80.0	80.0	75.0	0.0	0.0
80.0	75.0	75.0	0.0	0.0
80.0	70.0	75.0	0.0	0.0
80.0	65.0	75.0	0.0	0.0
80.0	60.0	75.0	0.0	0.0
80.0	55.0	75.0	0.0	0.0
80.0	50.0	75.0	0.0	0.0
80.0	45.0	75.0	0.0	0.0
45.0	45.0	75.0	0.0	0.0
40.0	45.0	75.0	0.0	0.0
35.0	45.0	75.0	0.0	0.0
30.0	45.0	75.0	0.0	0.0
25.0	45.0	75.0	5	0.0

Tabella 9: Selfsufficient_configuration_13_turbine

Excellent trade-off between tank size and hydrogen component ratings. Slight deficits emerge only with PEMEL below 30 kW.

14 turbine

PEMEL [kW]	Fuel Cell [kW]	H_2 Tank [kg]	P Deficit [kWh]	Q Deficit [kWh]
50.0	50.0	50.0	0.0	0.0
50.0	45.0	50.0	0.0	0.0
50.0	40.0	50.0	0.0	0.0
50.0	35.0	50.0	3.51	0.0
45.0	40.0	50.0	0.0	0.0
40.0	40.0	50.0	0.0	0.0
35.0	40.0	50.0	0.0	0.0
30.0	40.0	50.0	0.0	0.0
25.0	40.0	50.0	0.0	0.0
20.0	40.0	50.0	0.0	0.0
15.0	40.0	50.0	0.0	0.0
10.0	40.0	50.0	0.0	0.0
5.0	40.0	50.0	0.0	1.89

Tabella 10: Selfsufficient_configuration_14_turbine

Robust and compact setup. Slight power deficits appear when PEMEL drops significantly below 35 kW.

15 turbine

PEMEL [kW]	Fuel Cell [kW]	H_2 Tank [kg]	P Deficit [kWh]	Q Deficit [kWh]
50.0	50.0	50.0	0.0	0.0
50.0	50.0	45.0	0.0	0.0
50.0	50.0	40.0	0.0	0.0
50.0	50.0	35.0	0.0	0.0
50.0	50.0	30.0	0.0	0.0
50.0	50.0	25.0	0.0	0.0
50.0	50.0	20.0	4.29	143.44
50.0	45.0	25.0	0.0	0.0
50.0	40.0	25.0	0.0	0.0
50.0	35.0	25.0	0.0	0.0
50.0	30.0	25.0	1.58	0.0
45.0	35.0	25.0	0.0	0.0
40.0	35.0	25.0	0.0	0.0
35.0	35.0	25.0	0.0	0.0
30.0	35.0	25.0	0.0	0.0
25.0	35.0	25.0	0.0	0.0
20.0	35.0	25.0	0.0	0.0
15.0	35.0	25.0	0.0	17.39

Tabella 11: Selfsufficient_configuration_15_turbine

Highly efficient system. A tank size of 25 kg is sufficient in most configurations, with minimal power and thermal deficits only at the lowest PEMEL levels.

With 16 turbines, the system remains completely autonomous using only 1 kW PEMEL and 1 kW FC. The hydrogen subsystem becomes practically superfluous, only necessary in extreme backup cases or for external applications (e.g., mobility, grid support, chemical export).

Conclusion

- **Below 12 turbines**, system sizing becomes impractical due to oversized hydrogen requirements.
- **Between 12 and 15 turbines**, hydrogen plays a crucial role in ensuring resilience and self-sufficiency.
- **With 16 or more turbines**, the system can guarantee energy continuity with negligible hydrogen use—suggesting that the hydrogen subsystem may be excluded, or reallocated for other strategic uses.

This analysis provides a quantitative basis for selecting robust system configurations and clearly illustrates the scalability of the hydrogen system in response to renewable capacity. It also informs the next phase of the economic analysis, where configurations with **12,13, 14, and 15 turbines** will be explored in depth.

8 Economic Analysis of ZEESA Energy Configurations (12–15 Turbines + H_2 System)

This section presents a detailed techno-economic analysis of hybrid renewable energy system configurations proposed for the ZEESA (Zero Emission Energy System for the Arctic) project, designed for Ny-Ålesund, Svalbard. The settlement currently relies on diesel generators, making energy supply both costly and environmentally unsustainable. The ZEESA project seeks to replace diesel with an integrated wind and hydrogen system, supporting energy autonomy and emissions reduction under harsh Arctic conditions.

This economic assessment examines four scenarios, varying the number of 25 kW wind turbines (12 to 15 units), all coupled with a hydrogen system comprising a PEM electrolyzer, a high-pressure hydrogen tank, and a PEM fuel cell. The purpose is to evaluate economic feasibility, inform early design choices, and highlight the most promising pathway for investment. The results, while based on technical realism, represent a preliminary pre-feasibility study, to be refined in Phase 3 of the ZEESA project when actual procurement data, infrastructure layout, and potential incentive mechanisms will be available.

Methodology

This economic analysis is structured around the following framework:

2.1 Time Horizon and Discount Rates

A 20-year lifetime is assumed for the full system, consistent with international standards for renewable energy projects [64].

Discount rates of 3%, 5%, and 7% are applied to assess how financing conditions affect investment performance. These rates reflect public-sector loans (3%), base-case assumptions (5%), and conservative investor scenarios (7%).

Diesel Offset and Energy Valuation:

- The system offsets 238,778 kWh/year of electricity currently supplied by diesel generators.
- The avoided cost of diesel electricity is estimated at €0.519/kWh, which includes fuel, logistics, maintenance, and environmental costs in Arctic settlements [64].

Component Costs

The following unit prices are derived from recent literature and market analysis:

Wind turbines: €1,400/kW [65]

PEM Electrolyzer (30 bar): €1,600/kW [66]

PEM Fuel Cell: €3,500/kW [67]

Hydrogen tank (30 bar): €700/kg [68]

These values include equipment, installation, and basic system integration ("overnight cost").

Operating Costs (Annual OPEX)

Wind turbines: 2% of CAPEX/year

Electrolyzer: 3% of CAPEX/year

Fuel Cell: 4% of CAPEX/year

Hydrogen tank: 1% of CAPEX/year

Replacement Schedule

To maintain system functionality over 20 years:

PEM Electrolyzer: Full replacement at Year 10

PEM Fuel Cell: Full replacement at Years 7 and 14

Battery systems are already installed and not considered in CAPEX or OPEX

All components are assumed to be installed and commissioned in Year 0; no construction delays or inflation adjustments are included, consistent with a pre-feasibility "overnight" investment model [65].

Results

Configuration	CAPEX (€)	NPV @ 3% (€)	NPV @ 5% (€)	NPV @ 7% (€)	Payback @ 3% (yrs)	Payback @ 5% (yrs)	Payback @ 7% (yrs)	LCOE (€/kWh)
12 turbines	936,500	+119,000	−46,500	−173,000	16	16	16	0.196
13 turbines	713,000	+604,000	+394,000	+232,000	9	9	9	0.149
14 turbines	713,000	+633,000	+417,000	+252,000	8	8	8	0.149
15 turbines	801,000	+426,000	+231,000	+81,000	11	11	11	0.168

Tabella 12:Economic_Summary

Capital Expenditure (CAPEX) Breakdown
The investment includes procurement, delivery, and installation of all hydrogen-related and wind generation equipment. The 13 and 14 turbine configurations show the most favorable CAPEX-to-yield ratio due to higher capacity utilization without overdesign. The 12-turbine configuration has a higher CAPEX due to system oversizing and lower production efficiency [65][66].

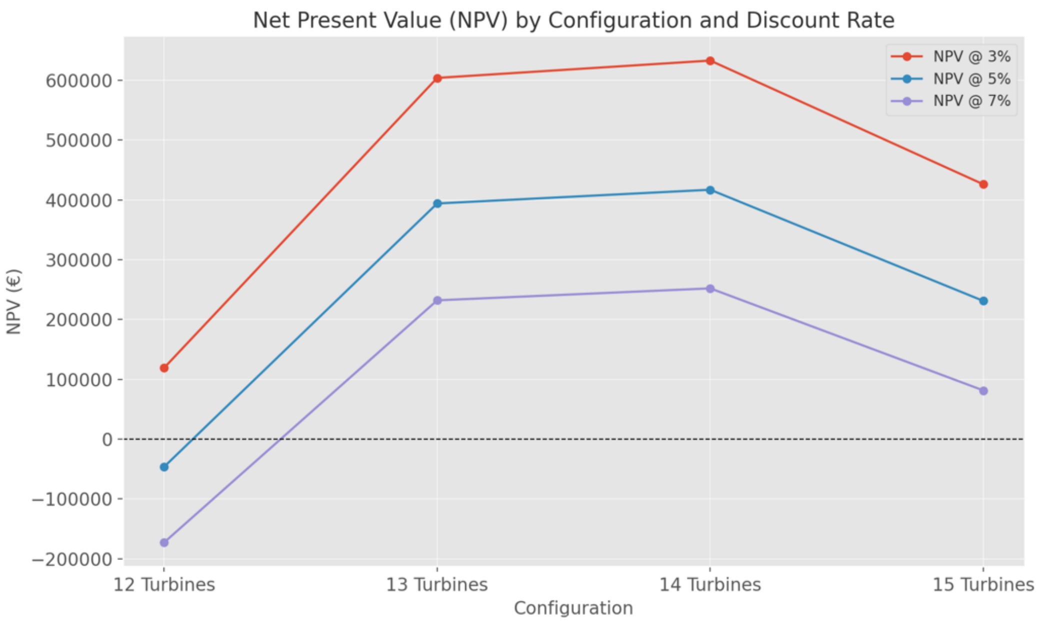

Figure 70: Net_Present_Value

Net Present Value (NPV)
NPV reveals which configurations yield long-term financial returns. The 13 and 14 turbine options show robust, positive NPV even at a 7% discount rate. A negative NPV for the 12-turbine system under higher discounting suggests limited viability without subsidies or performance improvements [64].

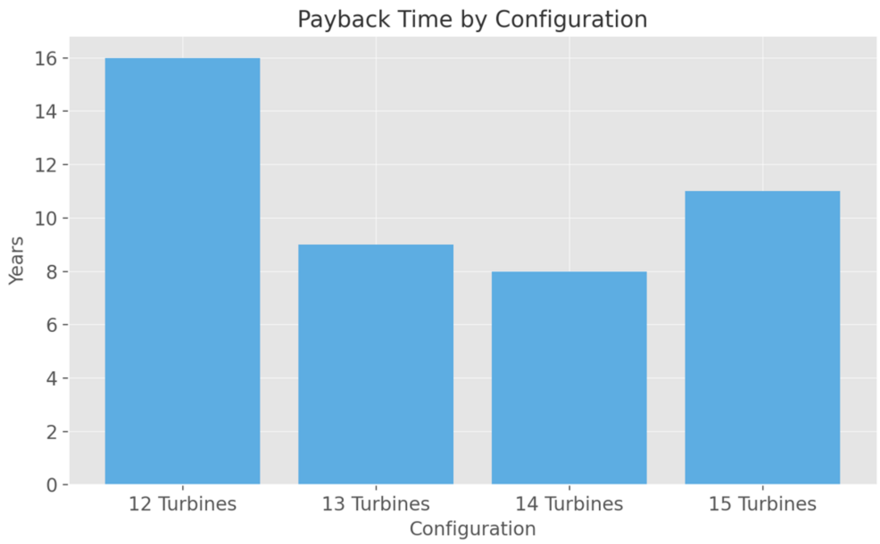

Figure71:Pay_Back_Time

Payback Time and Levelized Cost of Energy (LCOE)
13 and 14 turbines: payback achieved within 8–9 years
15 turbines: longer return time (11 years)
12 turbines: longest payback (16 years)
LCOE remains lowest for 13–14 turbines at €0.149/kWh, substantially outperforming diesel-based generation costs [64].

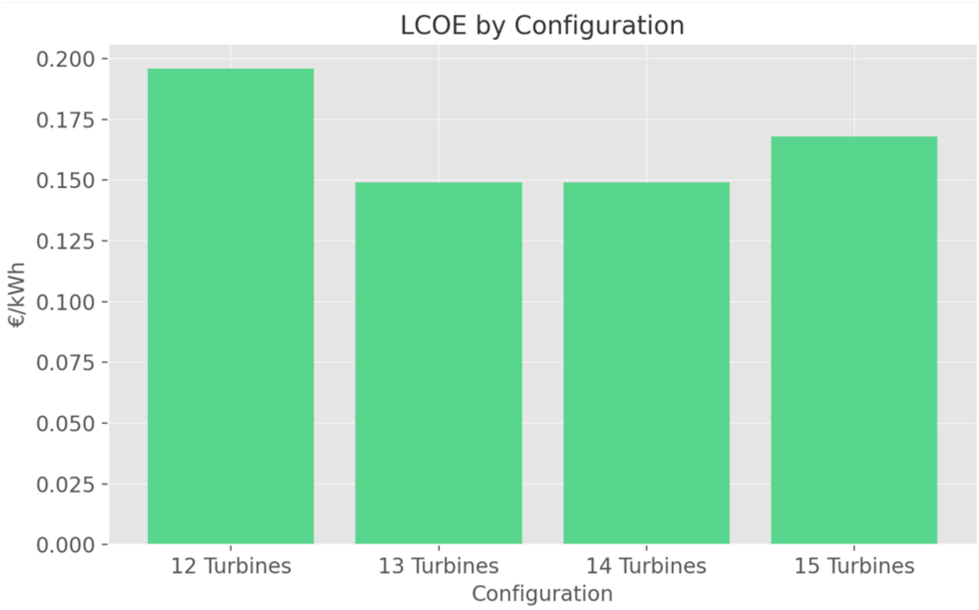

Figure81:Levelize_Cost_of_Energy

Conclusion

13 and 14 turbines offer the most favorable combination of return, cost, and resilience.

14 turbines stands out as the most balanced option in terms of NPV and system autonomy.

12 turbines is not advisable without grants or improved production factors.

15 turbines adds flexibility but with reduced economic efficiency.

Financing structure (e.g., WACC reduction via green bonds or development grants) can greatly enhance outcomes.

A full feasibility study (Phase 3) should expand this analysis by including environmental permitting, grid stability studies, and OPEX variations under extreme Arctic weather.

9 Conclusion

The main objective of this thesis was to size the electrolyzer, fuel cell, and hydrogen storage system in order to assess the technical and economic feasibility of achieving energy self-sufficiency in Phase 4 of the ZEESA project. This objective has been fully achieved.

The analysis carried out has demonstrated not only the technical viability of the system in the base case—where a PEM electrolyzer is used to produce hydrogen directly compressed to 30 bar (a solution chosen to minimize system complexity and maintenance needs, particularly during the winter months)—but also its resilience under more challenging conditions.

Even in less favorable scenarios, the integration of an adequate number of wind turbines confirmed the effectiveness of the proposed approach: hydrogen proves to be an ideal complementary energy vector, capable of ensuring full energy balancing. The results show that, with proper system design, it is possible to reach full annual energy self-sufficiency without resorting to fossil fuels.

It is hoped that this study will contribute meaningfully to the ongoing design decisions for Phase 3 and serve as a solid foundation for the implementation of Phase 4, planned in the coming years. The findings support the transition toward a fully renewable, sustainable, and replicable energy model, particularly in remote and climatically extreme environments.

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Appendix A – Python Code

<Full code from run_simulation.py - already included above>

Appendix B – manage_battery_then_electrolyzer.py

```
import logging

def manage_battery_then_electrolyzer(
    hour,
    Psurplus,
    SoC_battery,
    Pbattery,
    E_batt,
    eta_charge,
    SoC_max,
    Pelectrolyzer,
    eta_electrolyzer,
    HHV_H2,
    H2,
    Pelectrolyzer_min,
    Pelectrolyzer_max,
    battery_min_power=10
):
    """
    1) Charge the battery only if SoC < SoC_max and surplus > battery_min_power.
    2) If surplus remains, power the electrolyzer.
    """
    soc_prev = SoC_battery[hour-1] if hour > 0 else 0
    soc_prev = min(max(soc_prev, 0), SoC_max)
    E_available = E_batt * (SoC_max - soc_prev) / 100

    Pbattery[hour] = 0
    SoC_battery[hour] = soc_prev

    if soc_prev < SoC_max and Psurplus[hour] > battery_min_power:
        charge_possible = min(Psurplus[hour], E_available / eta_charge)
        charged = charge_possible * eta_charge

        new_soc = soc_prev + (charged / E_batt) * 100
        SoC_battery[hour] = min(new_soc, SoC_max)
        Pbattery[hour] = charged
        Psurplus[hour] -= charge_possible

    if Psurplus[hour] >= Pelectrolyzer_min:
        P_el = min(Psurplus[hour], Pelectrolyzer_max)
        Pelectrolyzer[hour] = P_el

        h2_prod = (P_el * eta_electrolyzer) / HHV_H2
        prev_h2 = H2[hour-1] if hour > 0 else 0
        H2[hour] = prev_h2 + h2_prod

        Psurplus[hour] -= P_el
    else:
        Pelectrolyzer[hour] = 0
        H2[hour] = H2[hour-1] if hour > 0 else 0

    return Psurplus, SoC_battery, Pbattery, Pelectrolyzer, H2
```

Appendix C – evaluate_boiler_cases.py

```
from manage_battery_then_electrolyzer import manage_battery_then_electrolyzer
```

```
from boiler_support_logic import boiler_support_logic

def evaluate_boiler_cases(
    hour,
    Psurplus,
    Qstorage,
    Qload_energy,
    eta_electrolyzer,
    Pelectrolyzer_min,
    Pelectrolyzer_max,
    Pbattery_max,
    SoC_battery,
    SoC_max,
    E_batt,
    eta_charge,
    H2,
    HHV_H2,
    Pelectrolyzer,
    Pbattery,
    battery_min_power=10
):
    """
    1) Use surplus electricity to meet thermal load Qload:
       - As long as Qload isn't satisfied and surplus remains.
    2) If Qload remains unmet, call boiler_support_logic.
    3) If Qload is satisfied and surplus remains, call
manage_battery_then_electrolyzer.
    Also returns Q_unsupplied.
    """
    surplus = Psurplus[hour]
    q_stored = Qstorage[hour]
    q_load = Qload_energy[hour]
    q_needed = max(q_load - q_stored, 0)
    Q_unsupplied = 0

    if surplus > 0 and q_needed > 0:
        use = min(q_needed, surplus)
        Qstorage[hour] = q_stored + use
        surplus -= use
        q_needed -= use

    if q_needed > 0:
        Qstorage, SoC_battery, H2, boiler_unsup = boiler_support_logic(
            hour,
            Qstorage,
            Qload_energy,
            SoC_battery,
            Pbattery_max,
            E_batt,
            H2,
            HHV_H2
        )
        Q_unsupplied = boiler_unsup
    else:
        Psurplus, SoC_battery, Pbattery, Pelectrolyzer, H2 =
manage_battery_then_electrolyzer(
            hour,
            Psurplus,
            SoC_battery,
            Pbattery,
            E_batt,
            eta_charge,
            SoC_max,
            Pelectrolyzer,
            eta_electrolyzer,
            HHV_H2,
            H2,
```

```
        Pelectrolyzer_min,
        Pelectrolyzer_max,
        battery_min_power=battery_min_power
    )
    surplus = Psurplus[hour]

Psurplus[hour] = surplus

return Qstorage, SoC_battery, H2, Psurplus, Pbattery, Pelectrolyzer, Q_unsupplied
```

Appendix D – boiler_support_logic.py

```
def boiler_support_logic(
    hour,
    Qstorage,
    Qload_energy,
    SoC_battery,
    Pbattery_max,
    E_batt,
    H2,
    HHV_H2,
    eta_fuelcell=0.7,
    eta_boiler=0.9
):
    """
    1) Use battery to meet remaining thermal load.
    2) Then use H2 (via fuel cell + boiler).
    3) Returns Q_unsupplied if there is still a deficit.
    """
    q_prev = Qstorage[hour-1] if hour > 0 else 0
    soc_prev = SoC_battery[hour-1] if hour > 0 else 0
    soc_prev = min(max(soc_prev, 0), 100)

    q_load = Qload_energy[hour]
    q_stored = q_prev
    q_needed = max(q_load - q_stored, 0)
    Q_unsupplied = 0

    if q_needed > 0 and soc_prev > 0:
        energy_avail = (soc_prev / 100) * E_batt
        q_from_batt = min(q_needed, energy_avail, Pbattery_max)
        SoC_battery[hour] = soc_prev - (q_from_batt / E_batt) * 100
        q_stored += q_from_batt
        q_needed -= q_from_batt
    else:
        SoC_battery[hour] = soc_prev

    prev_h2 = H2[hour-1] if hour > 0 else 0
    if q_needed > 0 and prev_h2 > 0:
        max_heat_h2 = prev_h2 * HHV_H2 * eta_fuelcell * eta_boiler
        q_from_h2 = min(q_needed, max_heat_h2)
        h2_used = q_from_h2 / (HHV_H2 * eta_fuelcell * eta_boiler)
        H2[hour] = prev_h2 - h2_used
        q_stored += q_from_h2
        q_needed -= q_from_h2
    else:
        H2[hour] = prev_h2

    if q_needed > 0:
        Q_unsupplied = q_needed

    Qstorage[hour] = q_stored
    return Qstorage, SoC_battery, H2, Q_unsupplied
```

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Questi ringraziamenti sono stati fatti con il cuore, sono stati scritti di getto, il mio flusso di pensieri e stato libero e autentico, e proprio per questo non ho voluto ne cambiarli ne correggerli per farvi vedere esattamente cosa penso di voi appena vi penso, quindi perdonate l'italiano, perdonate gli errori, perdonate tutto ma questa sono io.

io lo so che si dovrebbe ringraziare tutte le persone a cui si vuole bene ma lo sapete a me piace rompere le palle e andare controcorrente, quindi vorrei specificare che chiunque non sia stato ringraziato qua non e perché sia una persona meno importante per me, ma volevo rendere questi ringraziamenti speciali per le persone che mi hanno aiutata a conseguire questa laurea, a tutte le altre grazie di far parte delle mia vita.

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