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Assessment of a Hybrid Renewable Energy System Incorporating Wind, Solar, and Storage Technologies in Makkovik, Newfoundland and Labrador

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Abstract: This investigation addresses the critical challenge of devising robust and sustainable energy infrastructures by integrating renewable energy sources in Makkovik, Newfoundland, and Labrador. A hybrid renewable energy system (HRES) comprising wind turbines, photovoltaic (PV) solar panels, battery storage, and backup diesel generators was evaluated for its viability and efficiency. With the help of the HOMER Pro software, extensive modeling and optimization were conducted, aimed at reducing dependency on fossil fuels, cutting carbon emissions, and enhancing economic benefits via decreased operational costs. The results indicated that the energy demands of Makkovik could predominantly be met by the proposed system, utilizing renewable resources. Significant reductions in greenhouse gas emissions were observed, alongside improved cost-efficiency throughout the system's projected lifespan. Such outcomes demonstrate the system's capability to provide an environmentally friendly and technically viable solution, marking a substantial step towards energy resilience and sustainability for isolated communities. The integration of diverse renewable energy sources underlines the potential for substantial emission reductions and operational cost savings, highlighting the importance of innovative energy solutions in enhancing the sustainability and resilience of remote areas. This study contributes vital insights into optimizing energy systems for economic and environmental benefits, advancing the discourse on renewable energy utilization in isolated regions.

Keywords: HOMER Pro; Hybrid power; Wind energy; Solar energy; Canada; Newfoundland and Labrador (NL); Makkovik

1 Introduction

The pivotal shift towards renewable energy sources marks a significant stride in the global endeavor to combat climate change and foster sustainable development, combining the goals of enhancing energy security and mitigating the environmental impacts associated with traditional fossil fuel use into a compelling narrative for change. To integrate various energy sources in a way that guarantees a steady and continuous energy supply, the HRES has emerged as a feasible solution to the inherent intermittency and dependability difficulties of renewable energy [1–3]. Research indicates that integrating renewable and conventional energy systems in parallel, is more flexible and reliable than integrating them in series. This technique greatly lowers greenhouse gas emissions by enabling a variety of energy sources to cooperate harmoniously to fulfill varying energy demands. Furthermore, the vital role that energy storage technologies play in stabilizing power systems with high renewable penetration is becoming more widely acknowledged. These devices offer crucial ancillary services like peak shaving and frequency management [4].

The majority of the electricity produced in Canada is generated by renewable sources. However, almost all microgrids in isolated Southern Canadian communities disconnected from the main grid rely on fossil fuels to provide electricity. The study "Decarbonizing Canada's Remote Microgrids" examines Canada's significant transition away from fossil fuels and toward renewable energy sources, highlighting the necessity of this change to improve energy security and reduce environmental damage. It specifically tackles the difficulties faced by isolated communities that are cut off from Southern Canada's main power grid and nearly entirely dependent on fossil fuels for electricity. It emphasizes the critical need for creative energy solutions in these remote areas to facilitate sustainable development and achieve decarbonization [5].

The increasing reliance of isolated populations on conventional energy sources, particularly fossil fuels, raises serious concerns as we move toward more sustainable energy frameworks. Opeyemi [3] represents an analysis of Nigeria's energy consumption profile and offers an empirical foundation for thinking about the replacement of non-renewable and renewable energy sources. Due to high carbon emissions and resource depletion, this research draws attention to the overwhelming reliance on non-renewable energy sources, which make up a sizable percentage of the total energy mix. This raises issues regarding sustainability and the environment.

Makkovik, an Inuit community in Canada, isolated from the mainland, is a perfect example of this problem. Its reliance on diesel, a less practical and sustainable option for the environment, highlights how urgently we need creative energy solutions. Because of this, Makkovik is a great place for studies on the adoption of HRES, to create a model for sustainability and energy independence that can be applied to comparable towns across the globe. The situation in Makkovik, Newfoundland, and Labrador highlights the urgent need for creative energy solutions that are considerate of the unique geographical, as shown in Figure 1, and cultural factors of isolated places while also being sustainable. In addition to being a calculated step toward environmental preservation, the implementation of HRES in these areas will help them become energy-independent by lowering their need for expensive and environmentally damaging fossil fuel imports. This move is essential for helping isolated communities flourish socioeconomically since it provides a way to reduce energy expenses and lessen environmental effects. The socio-economic benefits of adopting hybrid energy systems are detailed in the study by Vurur [6].

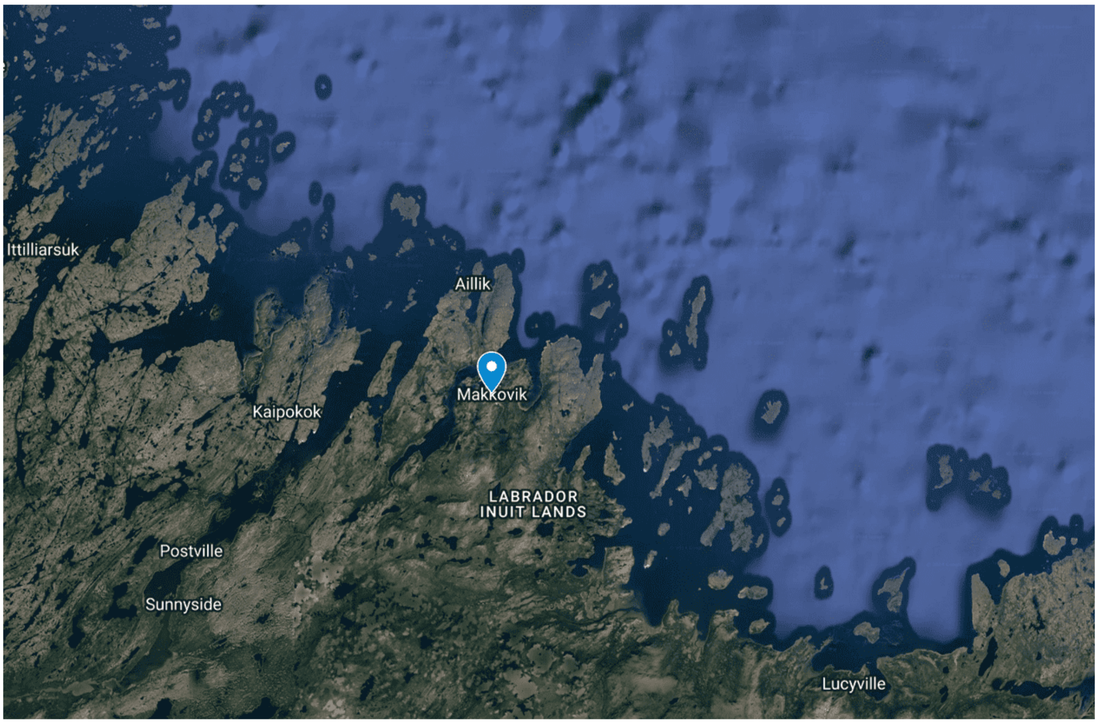

Figure 1. Map showing the position of Makkovik, NL

It is expected that Makkovik's HRES would bring about several socio-economic and environmental advantages, notably improving the community's standard of living and ecological impact. First, the transition to renewable energy sources like wind and solar offers a significant chance to create jobs. A workforce knowledgeable in renewable energy technology will be necessary for both the building phase and the continuing operation and maintenance of the energy system, in addition to trained and semi-skilled labor. This promotes employment and skill development locally, hence strengthening the economy [7]. Furthermore, the move to a renewable energy grid that is managed locally represents genuine energy independence. Less reliance on imported diesel fuel will allow the community to better manage its energy supply and lower the risks of supply chain interruptions and volatile fuel prices. The town is empowered by this energy production self-sufficiency, which guarantees a steady and dependable power supply to promote growth and development in the future. The environmental effects of switching to a HRES are significant, in addition to the financial ones. A significant improvement in air quality is anticipated since the decrease in diesel usage results in a direct reduction in the emissions of hazardous pollutants such as sulfur dioxide, nitrogen oxides, and particle matter. As a result of the reduced respiratory and cardiovascular disorders linked to air pollution, the public's health improves. In addition, by reducing greenhouse gas emissions, the initiative contributes to the larger objectives of climate action, establishing Makkovik as a model of environmentally conscious, sustainable living [8].

Beyond technological advancements, renewable energy solutions resonate intimately with the cultural ethos, long-standing traditions of sustainability, and environmental care intrinsic to Indigenous communities like Makkovik. The community's commitment to protecting their natural surroundings for future generations is evident from the lack of direct information on Makkovik's renewable energy initiatives. These initiatives also reflect the community's practices of inclusivity and collective decision-making, which are common among Indigenous communities worldwide. Similar situations can be found, for instance, in Australia, where Indigenous communities' shift to renewable energy has been framed as an empowerment tool that preserves cultural and environmental integrity while leveraging local knowledge to combat climate change [9]. The Moloka'i village in Hawaii is spearheading renewable energy projects driven by the philosophy that "the land is the chief, and we are the servants," highlighting a sustained dedication to environmental care [10]. Similar to this, the Igiugig village in Alaska combines renewable energy projects with traditional beliefs, making sure that these endeavors are sensitive to cultural differences and promote the community's long-term sustainability [11]. By drawing comparisons between these instances, it is plausible that Makkovik's strategy for renewable energy not only seeks to replace traditional energy sources but also acts as evidence of the community's tenacity, independence, and commitment to preserving its natural and cultural heritage. These initiatives highlight how crucial it is to combine cutting-edge technology with traditional wisdom and values to empower Indigenous people everywhere, including Makkovik, and pave the way for a sustainable future.

This analysis underscores the significant impact of renewable energy systems on economic development and sustainability, offering a broader perspective on the benefits of hybrid systems beyond energy generation. Furthermore, using renewable energy in these contexts supports global sustainability objectives and makes a substantial contribution to the decrease of greenhouse gas emissions and the improvement of environmental quality worldwide.

In this study, a hybrid energy system for Makkovik that makes use of solar and wind energy in addition to battery storage options along with diesel generators is proposed. With HOMER Pro, the design and analysis process are carried out to offer the area a cost-effective, efficient, and sustainable energy solution.

The paper is structured as follows: Section 2 contains the literature review, the methodology is explained in Section 3, the load profile and local resources are examined in Section 4, the hybrid system design is explained in Section 5, the results and discussion are presented in Section 6, and the study is concluded in Section 7.

2 Literature Review

As communities worldwide grapple with the effects of climate change and work toward energy independence, the switch to renewable energy is critical. Makkovik presents particular energy issues that highlight the pressing need for creative and sustainable energy solutions, just like many isolated communities throughout the world. This study delves further into these issues by investigating how HRES might transform the way remote people obtain their energy and electricity.

Makkovik is a small Inuit village home to about 360 people [12]. The Inuit Community of Makkovik is situated roughly 210 kilometers northeast of Happy Valley-Goose Bay, Labrador, at coordinates 55°07'N and 59°03'W. Makkovik is situated from Cape Makkovik into the inland [13]. Geographically isolated and with little access to centralized grid infrastructure, isolated communities like Makkovik have difficulties finding affordable and dependable electricity. Energy security is compromised, and environmental deterioration is exacerbated by traditional fossil fuel-based generators, which also result in high energy costs. By combining renewable energy sources with conventional production and energy storage technologies, hybrid energy systems that offer resilient and sustainable energy solutions for isolated communities are becoming more and more popular as a response to these difficulties. A thorough exploration of the field of renewable energy research is undertaken in this literature review, with a particular emphasis on hybrid systems that combine the benefits of solar, wind, and energy storage technology. Our analysis spans a wide range of research, from the economic and technological feasibility of hybrid energy systems to their environmental effects, and demonstrates the rapid advancement of knowledge and innovation in this subject.

The use of renewable energy technology has been researched by academics from several jurisdictions. Most of them focused mostly on the use of solar energy, wind turbines, and batteries in conjunction with the planning, analysis, and evaluation of various hybrid power systems in various configurations. The potential of combining energy storage technologies like batteries and hydrogen fuel cells with renewable energy sources like solar PV, wind turbines, hydroelectric generators, and biomass systems has been highlighted in recent literature on hybrid energy systems for remote communities.

Several studies stand out in the rapidly changing field of renewable energy research for their contributions to the understanding and advancement of hybrid energy systems, providing complementary information to the fundamental research underpinning the Makkovik Island project. Benchmarks from the deployment of comparable systems in St. Brendan's NL, Grey River NL, and Ramea Island, and comparative studies on Al-Muthana are helpful in the development of a resilient and sustainable HRES for Makkovik. Each project highlights the flexibility and promise of hybrid systems in meeting the particular energy demands of remote communities as they are customized to fit their particular geographic and socioeconomic situation. The study [14] demonstrated integrating wind turbines and solar panels with HOMER Pro-optimized diesel generators as a complement in St. Brendan's, NL. This model offered Makkovik a blueprint for utilizing its local wind and solar potential by demonstrating that it is feasible to integrate renewable sources and greatly reduce diesel usage. Kandil et al. [15] concentrated on integrating PV panels with diesel generators that were already in place for Grey River, NL. The study demonstrated the system's capacity to sustain stability and power production in the face of load changes by using MATLAB Simulink for dynamic simulations and HOMER Pro for steady-state analysis. This highlights the significance of adaptable energy solutions in Makkovik and similar areas where seasonal variations in energy demand occur. The adoption of a broader hybrid approach by Kotian et al. [16], which includes diesel generators, solar, wind, and battery storage for Ramea Island, NL, shows how different energy sources may improve system resilience and dependability. This technique, which suggests that a diverse energy plan may provide a steady power supply even in difficult circumstances, is especially pertinent to Makkovik. Issa et al. [17] highlights the crucial role that thorough system modeling and optimization play in obtaining both financial and environmental efficiency by providing insights into the design and ideal size of a hybrid power system in Al-Muthana using the HOMER simulator. Makkovik believes that project profitability and resource efficiency might be maximized by using a similarly stringent design method. The importance of context in the development and use of HRES is highlighted by this comparative analysis. It supports the case for a more nuanced interpretation of the Makkovik system, promoting a model that not only attends to the community's unique energy requirements but also adds to the international conversation on sustainable development in isolated places.

The study by Ameur et al. [18] on dynamic forecasting models for PV/GES systems shows how improved predictive analytics can result in significant cost and energy savings. Furthermore, the techno-economic analysis of an optimized hybrid system on Malawali Island, Malaysia, that includes diesel generators, PV cells, wind turbines, and batteries highlights the viability and financial benefits of implementing a variety of energy sources in remote areas, supporting the systems' relevance to Makkovik's energy environment [19].

The feasibility and environmental advantages of combining different energy sources are highlighted by recent research in renewable energy technology. For instance, studies [20–22] suggest that hybrid energy systems can improve energy access, lower greenhouse gas emissions, and increase energy resilience in remote locations while remaining economically and technically feasible. Also, Ahmadi et al. [23] offers a thorough approach to assessing the economic and environmental effects of hybrid energy systems, highlighting the vital role that sustainable design plays in attaining energy independence and reducing environmental impacts. De la Cruz-Soto et al. [24] highlights the importance of Power to Gas to Power (P2G2P) systems in improving microgrid sustainability through intercessional energy storage and notable reductions in CO_2 emissions. It does this by presenting a techno-economic analysis of a hydrogen storage system within a microgrid in Baja California, Mexico. This study underscores the transformative potential of utilizing advanced energy storage, management, and predictive analytics within hybrid energy systems. Recent developments in the field of optimizing renewable energy for remote and off-grid communities provide an excellent example of an environmentally friendly and long-lasting off-grid energy system. Their study, which presents a hybrid system with PV arrays, wind generators, and battery storage, successfully met the community's energy needs while achieving almost total grid autonomy. Ghadirinejad et al. [25] demonstrates a system that can provide 99.9% of the annual electricity needs using particle swarm optimization (PSO) techniques validated with HOMER Pro software. This highlights the viability of attaining high reliability and sustainability in energy provision through sophisticated optimization techniques.

The conversation on the viability and optimization of hybrid energy systems in isolated and island communities is further enhanced by recent research. For instance, in the study by Costa and Villalva [26], the possibility of integrating renewable energy sources into small island communities is explored. The importance of energy storage systems in maintaining a steady supply of electricity is emphasized. The study presents a strong argument for the use of hybrid systems to achieve sustainable electrification by highlighting the efficiency of combining PV systems with diesel generators and the critical role that batteries play in stabilizing the energy supply. Seedahmed et al. [27] examines the integration of wind energy, diesel generators, fuel cells, and batteries in a hybrid energy system designed to electrify a rural cluster in western Saudi Arabia. The techno-economic study is thorough. This study examines two hybrid setups and a diesel-only design, evaluating the environmental and economic feasibility of each using HOMER Pro software. The best combination of wind, diesel, fuel cell, and battery is shown in the results to be the most cost-effective and environmentally benign option, with a notable decrease in Net Present Cost (NPC) and CO_2 emissions when compared to conventional diesel systems.

Miao et al. [28] used HOMER Pro and the reference point approach in multi-criteria decision analysis to plan an island microgrid system, with an emphasis on the integration of economic, resilience, energy, and environmental factors to discover optimal configurations. This strategy is in line with creating a reliable and sustainable energy source for remote communities. Beyene et al. [29] explores the viability of grid-integrated hybrid systems, which combine modern storage technologies with solar and wind energy sources to provide distant communities with a reliable and sustainable electricity supply. It emphasizes how important energy storage is to reduce the erratic nature of renewable energy sources and raise overall power supply reliability. A techno-economic analysis of a standalone hybrid system on Donoussa Island, Greece, is carried out by the study contained in the study by Katsivelakis et al. [30]. Different scenarios are explored to determine the best environmentally and economically sustainable configuration. The research shows how PV arrays, wind turbines, and diesel generators can be combined to achieve a high rate of renewable energy penetration, drastically reduce dependency on fossil fuels, and lower energy costs using HOMER Pro software. A thorough investigation of the design and analysis of a hybrid stand-alone microgrid for an industrial facility in Iraq is included in the study described in Bhatti et al. [31]. This study makes use of HOMER Pro for hybrid microgrid design and optimization, PVsyst for comprehensive PV plant design, and SAM for performance analysis. It demonstrates how the method may cut CO_2 emissions dramatically, roughly 1811.6 tons over 30 years, and emphasizes the possibility of producing renewable energy.

A unique hybrid energy system for Salemo Island was created using Homer Pro software in the research by Mansur [32]. It was shown by the research that the LCOE of the hybrid system could be reduced to 1,306 IDR/kWh by adding 120 batteries and another 200 kWp Solar Power Plant (SPP). In addition to highlighting the many benefits of integrating renewable resources in remote locations, this approach also shows how a well-considered hybrid system design can significantly improve economic efficiency and reliability.

Farahmand et al. [33] provide an in-depth examination of Canada's potential contribution to Europe's energy problems through the export of hydrogen, in line with its 2050 carbon neutrality targets. This assessment carefully breaks down the downstream elements of the Canadian hydrogen supply chain, examining elements, decision-making procedures, and sustainability factors. With practical conclusions, it suggests ways to improve industry practices, policy formation, and research to increase the sustainability and efficiency of the hydrogen supply chain and support Canada's environmental goals.

Sakthi et al. [34] highlight NL's ability to produce sustainable hydrogen, which is important to consider given the increased concerns about energy security brought on by the conflict between Russia and Ukraine. The analysis highlights NL's distinct advantages and strategic location as critical to contributing to Europe's energy solutions by carefully examining the body of research on the province's hydrogen potential. It looks at the sources, production processes, storage alternatives, and distribution mechanisms of hydrogen, providing business executives, decision-makers, and academics with information on how to strengthen NL's position in international energy sustainability initiatives. The study also points out current research gaps and makes recommendations for how to proceed with creating NL's all-encompassing hydrogen plan to help the state reach net-zero emissions. An extensive case study on developing a hybrid power system using Homer Pro software for Nain, Newfoundland, and Labrador, is presented by Kotian and Ghahremanlou [35]. It demonstrates how diesel, wind, and solar energy may be integrated, highlighting the value of renewable energy sources in enhancing the sustainability and dependability of power infrastructure in isolated areas. Dr. Jean-Paul Pinard and collaborators' "Potential for Wind Energy in Nunavut Communities" [36] thoroughly evaluate the viability of wind energy in Nunavut. It maps out the potential for wind resources using information from Environment Canada and measurements from local airports, concentrating on the technical and financial viability of installing wind turbines. This study finds localities that show promise for wind energy projects. It does this by evaluating the economic and environmental effects of the projects using HOMER and RETScreen modeling.

New developments underscore the vital role dynamic system management and optimization strategies play in improving the resilience of hybrid energy systems for remote communities. HOMER software is an important tool for the analysis and optimization of renewable energy integration in the process of creating a full hybrid energy system for Makkovik Island. This work is placed in a wider context by the novel methodologies and conclusions from recent investigations. For example, the complexity of the balance between renewable energy integration and grid stability and HOMER's role in evaluating dynamic power management solutions for AC microgrids are highlighted in the study by Nagaraju et al. [37]. Similarly, Linda et al. [38] use HOMER for energy output simulations and stresses optimizing wind turbine designs for effective hydrogen generation. This study provides important information for Makkovik's renewable energy plan by highlighting the significance of choosing the ideal turbine heights to maximize hydrogen generation. HOMER's use in the research by Wang et al. [39] provides additional evidence of the program's use in raising the power electronic components of hybrid systems' operational efficiency. This work offers a framework for improving DC-DC converters' dynamic performance, which is essential for guaranteeing the smooth integration of diverse energy sources. With the help of HOMER software and fuzzy logic, the study by Kamal et al. [40] present a unique framework for microgrid pre-installation assessments. This approach effectively improves the cost-effective and environmentally friendly energy supply for remote places.

Table 1. Literature review summary

			System						Metric Parameter	
Reference	Location	Type	Wind	DG	Battery	PV	Fuel Cell	Software Used	NPC	COE
12	Iran	Hybrid System	✓	×	✓	✓		Homer	✓	✓
13	N/A	Hybrid System	×	×	×	✓	×	×	×	×
19	Western Saudi Arabia	Hybrid System	✓	✓	✓	×	✓	Homer	✓	✓
24	N/A	Hybrid System	×	✓	✓	✓	×	Homer	✓	✓
27	Nain, NL	Hybrid System	✓	✓	✓	×	×	Homer	✓	✓

A summary of some of the studies conducted in several locations using different combinations of hybrid systems is provided in Table 1. Although the development of hybrid systems has been the subject of several international case studies, there is a particular void in the literature about the design and implementation of such systems in Makkovik, Newfoundland, and Labrador. To close this gap, this study suggests creating a customized hybrid energy system for Makkovik that makes use of solar and wind energy in addition to battery storage options. With HOMER Pro, the design and analysis process are carried out to offer the area a cost-effective, efficient, and sustainable energy solution.

3 Methodology

The research employed a methodical approach, starting with an in-depth review of existing literature. Subsequently, comprehensive data collection was conducted, which cleared the path for detailed simulations and analyses. The HOMER Pro program was utilized to do simulations to ascertain the hybrid systems' optimal design.

A variety of engineering programs were used in this study to model and construct a hybrid energy system. Based on extensive research from the website of the NL government and geographic data from Google Maps, the study concluded that the most practical possibilities for producing electricity in the area are solar and wind power. The selection of HOMER Pro was based on its strong capabilities for renewable energy resource optimization. Figure 2 below shows the flow chart for the project.

First, we defined Makkovik's geographical location and profile of energy use, integrating regional climate data to approximate actual circumstances. We next conducted a thorough evaluation of renewable resources, properly estimating the energy potential by incorporating precise solar irradiance and wind speed data from NASA into the model. Performance, affordability, and environmental compatibility were carefully considered while choosing components, which included backup diesel generators, solar PV, wind turbines, and battery storage. The HOMER Pro system setup then made it easier to simulate different configurations and optimize for dependability, sustainability, and cost-effectiveness. The proposed design's economic feasibility and environmental effects are extensively examined using an optimization process that is based on certain criteria, as outlined in our methodology. These criteria include NPC, LCOE, and the degree of renewable integration.

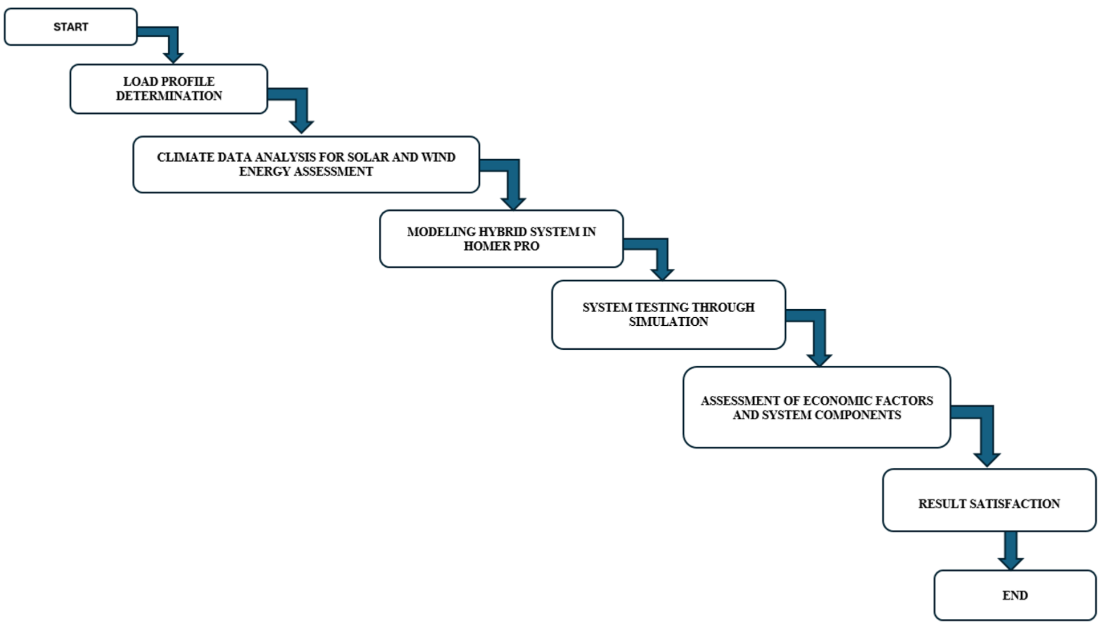

Figure 2. Flow chart of the research

4 Data Collection on Load Profiles and Local Resources

In this section, the details of the Load Profile, Wind Energy potential, and Solar energy potential of Makkovik are explained in detail.

4.1 Electrical Load Profile of Makkovik

Modeling the load profile is crucial for determining the optimal size and selection of renewable energy sources. Since the Makkovik community's power usage was not publicly available, a load profile was developed by modifying the load profile of a comparable community whose data was available, accounting for the number of homes in each location. The analysis considered all pertinent characteristics of the system components and the precise location of the Makkovik installation; hence, the electricity usage profile shown in Figure 3 is a reasonable estimate. The average load consumption is found to be 5454.20 kWh/day, with a peak load of 563.03 kW.

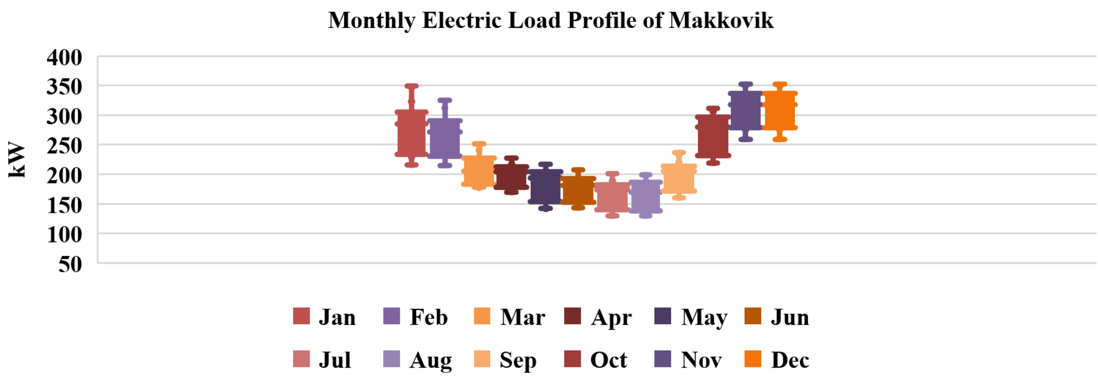

Figure 3. Electric load profile

4.2 Makkovik's Wind Energy Potential

The monthly wind speed values for the wind power source are shown graphically in Figure 4, which was also obtained from NASA Surface Meteorology. The average annual wind speed is found to be 8.53 m/s.

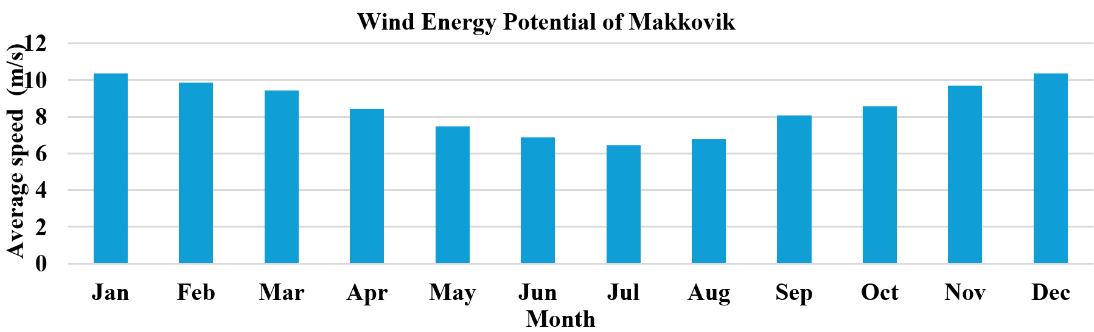

Figure 4. Wind energy potential of Makkovik

4.3 Makkovik's solar energy potential

NASA Surface Meteorology provided solar radiation data for Makkovik. Figure 5 shows the monthly values for the clarity index. The average annual solar radiation at that site was determined to be 2.92 kWh/m^2/day. According to the information, there was a notable increase in solar radiation from March to October, which produced enough energy to produce a sizable amount of electricity.

5 System Design

In this section, the schematic design of the system is provided along with the details of each selected component.

For the design and cost analysis of hybrid energy systems, HOMER Pro software is an excellent and well-known tool for precisely sizing these kinds of systems, and it has a large database with a variety of wind turbines and converters to make the selection process easier. A visual illustration of the interrelationship of the system's components is provided by HOMER Pro, as seen in Figure 6. An effective DC to AC power conversion is ensured

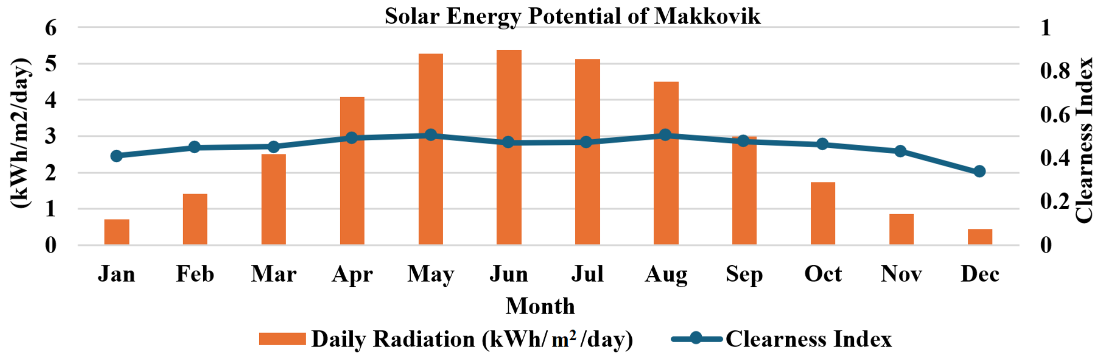

Figure 5. Solar energy potential of Makkovik

by converters, as shown in this diagram that shows how wind turbines and diesel generators are integrated with the AC busbar. These datasets serve as the foundation for creating a hybrid energy system that is specifically suited to Makkovik's climate. The details of the components used in the system are given in Tables 2-6.

Several fail-safes and contingencies are necessary to increase Makkovik's HRES's resilience against extreme weather occurrences. First, uninterrupted operation in inclement weather is ensured by the integration of sturdy wind turbines and solar panels that are made to survive harsh weather conditions like strong winds and heavy snowfall. An intelligent battery management system that can optimize charge and discharge cycles would also be beneficial to the system since it would lengthen battery life and improve performance during prolonged periods of low sunshine or wind. Adding redundant parts to the system, such as an auxiliary diesel generator and battery storage, can ensure energy delivery even if one component fails. Technologies for predictive maintenance and real-time monitoring, which may anticipate possible system breakdowns and enable preventive measures, are equally crucial. When combined, these steps would strengthen the system's robustness and dependability, protecting the community's energy supply from the unpredictable nature of severe weather occurrences.

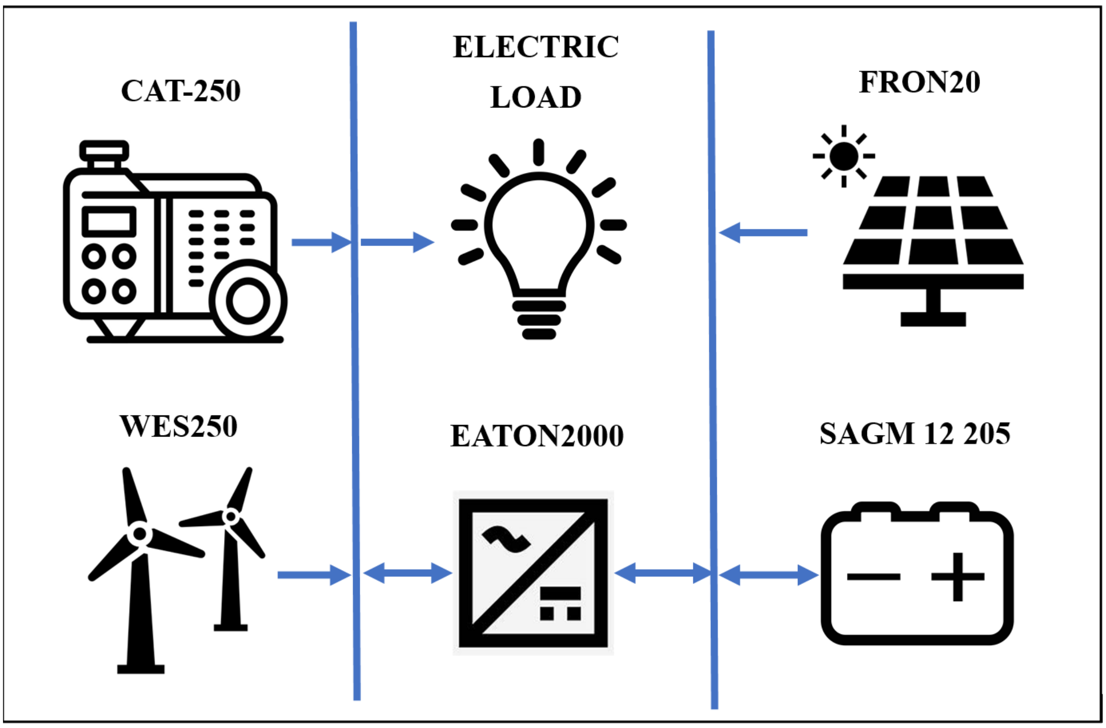

Figure 6. Schematic of the proposed system using HOMER Pro

5.1 PV Panels

PV panels are the cornerstone of the Makkovik hybrid energy system's electricity generation. The 1 kW capacity Fronius Symo 20.0-3-M with generic PV panels that were chosen to have a capital cost of $3,000 per. It is expected that these panels will last for a significant 25 years. The replacement costs are estimated at $3,000 per panel after considering lifecycle costs. This amount accounts for the cost of probable future market pricing as well as technological developments. With an estimated operation and maintenance (O&M) of $10/year, solar energy is economically viable and should be considered in Makkovik's long-term energy planning. Preventive maintenance activities, such as routine cleaning and inspections to reduce efficiency losses from environmental waste, are what define their O&M expenses the most. Apart from that, a significant portion of the long-term maintenance cost is associated with the inverter, a crucial component that has to be replaced over the panel's lifespan.

Given their excellent efficiency and compatibility with the chilly, fluctuating light conditions characteristic of Makkovik's environment, Fronius Symo 20.0-3-M solar panels were chosen. Their sturdy construction guarantees resilience to severe weather, which enhances the system's dependability during its anticipated 25-year operating life.

Table 2. HOMER fronius symo 20.0-3-M details

Quantity	**Value**
Name	Fronius Symo 20.0-3-M Generic PV
Rated Capacity	20kW
Capital Cost	$3000,000
Replacement Cost	$3000,000
O&M	$10/year
Manufacturer	Fronius
Lifetime	25 years

5.2 Wind Turbine

A WES 30 [250kW] wind turbine with a 20-year lifespan and a 48-meter hub height is used in the simulation. The initial capital cost of this turbine is $550,000; replacement costs are $500,000; and yearly maintenance costs are $40,000. Wind turbines provide distinct maintenance difficulties, particularly because of their intricate mechanical design and exposure to inclement weather. Lubrication, tension adjustments, and blade integrity checks are examples of preventive maintenance. The total O&M expenses of the turbines are impacted by the need for planned replacements due to the longevity of some mechanical elements.

The WES 30 [250kW] wind turbines were selected because of their capacity to function well in Makkovik's erratic wind patterns and chilly weather. With a 250-kW rated capacity, the WES 30 should be able to provide a sizable power output and help Makkovik meet its energy demands. Given Makkovik's wind profile, the turbine's capacity indicates that it is intended for medium to high wind speeds. Based on its selection, it appears to provide a good mix between initial investment and ongoing operating savings.

Table 3. HOMER Pro WES 30 [250kW] wind turbine details

Quantity	**Value**
Name	WES 30 [250kW]
Rated Capacity	250kW
Capital Cost	$550,000
Replacement Cost	$500,000
O&M	$40,000/year
Manufacturer	Wind Energy Solutions
Lifetime	20 years
Hub Height	48

5.3 Generator

During instances when wind or solar power generation is limited, diesel generators are included as a backup to produce electricity. The model considers the impact of fuel prices on the best configuration for the system and includes one generator: a CAT-250 kW, 60 Hz-PP. To achieve economic viability, the financial factors of the CAT-250 kW generator are thoroughly addressed. Given the estimated lifecycle expenses of the generator, a replacement cost of $24,000 has been set in addition to the initial capital cost of $28,000. The estimated cost of operational maintenance is $20 per operating hour, which impacts the hybrid system's overall optimization and adds to the overall cost of operation. To ensure operational preparedness, the generators need regular maintenance. This includes checking the engine, changing the oil, and replacing worn-out parts to keep the generator running when it's needed most. There is a 1.79 $/L fuel price. Due to its fuel economy, dependability, and ease of maintenance, a CAT-250 kW diesel generator is used as a vital backup system. Enhancing the robustness of the system, this component guarantees a continuous power supply during periods of low wind and solar output.

Table 4. HOMER Pro CAT-250kV diesel generator details

Quantity	Value
Name	CAT-250kW-60Hz-PP
Capacity	250kW
Fuel	Diesel
Capital Cost	$28,000
Replacement Cost	$24,000
O&M	$20/op. hour
Fuel Price	$1.79/L
Minimum Load Ratio	25%

5.4 Battery

In an HRES, batteries are a crucial component that acts as a buffer to improve grid stability. They attain this by storing surplus energy during times of high renewable production and supplying power at times of high demand or inadequate energy generation from renewable sources. An energy storage solution in the form of a Trojan SAGM 12 205 model has been chosen for the scenario under consideration. This given battery has a string size of 66 and a nominal voltage of 12 volts. It also has a capacity of 219 ampere-hours. Its initial state of charge, which is set at 100%, is anticipated to be fully charged at the outset. This setup comprises two to eighteen of these batteries in simulations. A battery replacement will cost $500, but the initial outlay for each battery is set at $600. For every battery, $50 is set aside every year for maintenance costs. Monitoring system performance, making sure the atmosphere is ideal, and cleaning the terminal are all part of maintenance. Since batteries have a limited operational life, replacing them eventually will cost a substantial portion of the system's operating budget.

With its exceptional resilience to temperature changes and low maintenance requirements, the Trojan SAGM 12 205 battery is a perfect fit for Makkovik's variable renewable energy system. It also provides excellent energy storage efficiency. Its extended service life and capacity to recover from deep discharges are guaranteed by its deep-cycle application design, which increases the dependability of systems that rely on intermittent energy sources. Priority should be given to safety and environmental concerns, and AGM technology lowers the possibility of leaks. This battery is a wise solution to meet Makkovik's energy requirements due to its affordability and compatibility with renewable technologies.

Table 5. HOMER Pro Trojan SAGM 12 details

Quantity	Value
Name	Trojan SAGM 12 205
Nominal Voltage	12V
Nominal Capacity	2.63kWh
String Size	66
Voltage	792
Maximum Capacity	219Ah
Capital Cost	$600
Replacement Cost	$500
O&M	$50/year
Initial state of charge	100%

5.5 Converter

In the Makkovik hybrid energy system design, a bidirectional converter, specifically the Eaton2000 model, is used. The power output of the converter is 1 kW. Its lifespan is fifteen years. The converter costs $6,000 to purchase, $4,500 to replace, and approximately $100 in maintenance each year.

Table 6. HOMER Pro Eaton2000 details

Quantity	Value
Name	Eaton Power Xpert 2000kW
Capital Cost	$6,000
Replacement cost	$4500
O&M	$100 / year
Lifetime	15 years

6 Results and Discussion

This section discusses the results of the HOMER Pro simulation for the proposed hybrid system. Based on 8698 solutions simulated by Homer Pro, the best one was chosen.

6.1 Homer Pro Selected System

With the help of Homer Pro, a large portfolio of possible hybrid system designs was created, outlining a variety of parts and important performance indicators like operational expenses, NPC, LCOE, and initial setup costs. Table 7 provides us with the ideal system configuration based on the platform's insights into various configurations and their effects.

Table 7. HOMER Pro selected system architecture

Component	Name	Size	Unit
Generator#1	CAT-250kW-60Hz-PP	250	kW
PV	Fronius Symo 20.0-3-M	6.30	kW
PV Dedicated Converter	Fron20 Converter	20.0	kW
Storage	Trojan SAGM 12	9	strings
Wind Turbine	WES 30 [250kW]	1	Ea.
System Converter	Eaton Power Xpert 2000kW	209	kW
Dispatch Strategy	HOMER Cycle Charging		

6.2 Electrical Summary

The power system's yearly data is displayed in Figure 7, which indicates that there is a 75,726kWh excess energy generated, a 514kWh unmet electric load (i.e., demand not satisfied), and a 1,981kWh capacity shortage (i.e., the deficit in generation capacity).

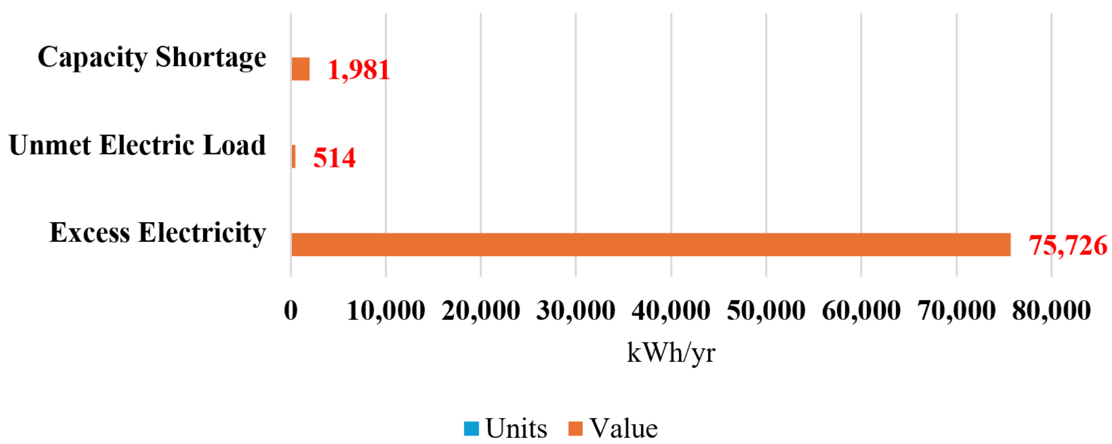

Figure 7. Excess electricity, unmet electric load, and capacity storage of the system

Table 8 shows the annual output for each component of the system. The highest power, about 55.8% of the total power, was generated by the wind turbines. The PV panels generated about 7,966 kWh annually, whereas the diesel generator produced 917,038 kWh/h. The overall energy generated was 2,090,604 kWh/year. The electrical analysis of the system in Homer Pro is shown in Figure 8.

Table 8. Annual production of each component

Component	Production (kWh/yr)	Percent
Fronius Symo 20.0-3-M with Generic PV	7,966	0.381
CAT-250kW-60Hz-PP	917,038	43.9
WES 30 [250kW]	1,165,600	55.8
Total	2,090,604	100

The annual distribution of energy consumption within the system is shown in Table 9, with the AC Primary Load accounting for all of the electrical demand at 1,990,269 kWh/year. This consumption pattern is significant, particularly because neither the DC Primary Load nor the DC Deferrable Load have any usage history. The AC Primary Load's dominance highlights its vital significance in the energy consumption of the system. These kinds of findings are critical for improving energy-saving initiatives and developing load management solutions. Additionally, the data forms the basis for determining how best to utilize excess electricity or address any capacity shortages that may be found, which eventually helps to support more strategic energy use planning that maximizes system performance and supports energy sustainability.

Table 9. Annual consumption table

Component	Consumption (kWh/yr)	Percent
AC Primary Load	1,990,269	100
DC Primary Load	0	0
Deferrable Load	0	0
Total	1,990,269	100

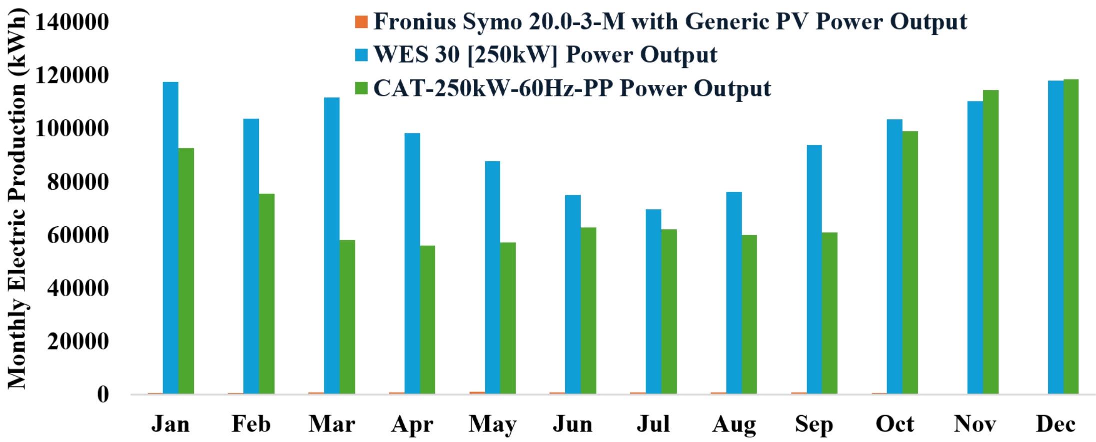

Figure 8. Electrical analysis - HOMER Pro

6.3 Fuel Summary

Important quantitative facts about fuel use over a given period are presented in Table 10. 360 tons of diesel were used overall. The average daily consumption was found to be 0.986 tons, or roughly 0.0411 tons per hour. These numbers offer an insightful perspective on trends in fuel consumption. For a variety of research, planning, and operational tasks, these insights are essential in industries that depend on diesel-powered machinery and vehicles. Figure 9 shows the graphical representation of the fuel summary.

6.4 Cost Summary

The financial analysis included in Table 11 and Figure 10 outlines the NPC of capital, operational, and replacement expenses, and salvage values for every system component. The CAT-250kW-60Hz-PP component's total NPC of $1.33M represented the overall cost incurred throughout the project. Interestingly, at $925,050, the Trojan SAGM 12 205 was the largest single investment. The total NPC of the complete system was determined to be $5.25 million. Most of the expenses were ascribed to the initial capital outlay and continuing operational costs, highlighting the financial aspects that are essential for evaluating the project's sustainability.

Table 10. Fuel summary

Quantity	Value	Units
Total Feedstock Consumed	360	tons
Avg Feedstock Per Day	0.986	tons/day
Avg Feedstock Per Hour	0.0411	tons/hour

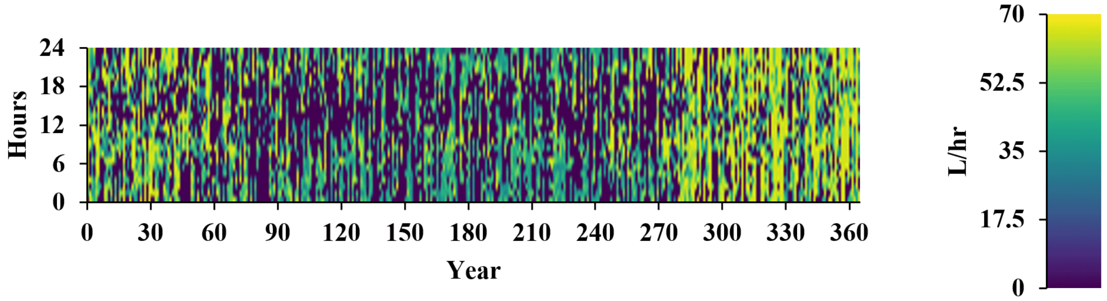

Figure 9. Graphical representation of fuel summary

Table 11. NPC of all the components

Name	Capital ($)	Operating ($)	Replacement ($)	Salvage ($)	Resource ($)	Total ($)
CAT-250kW-60Hz-PP	28,000	1.29M	18,108	-5,318	0.00	1.33M
Eaton Power Xpert 2000kW	1.25M	269,604	398,171	-74,940	0.00	1.84M
Fronius Symo 20.0-3-M with Generic PV	18,908	814.78	0.00	0.00	0.00	19,723
Trojan SAGM 12205	356,400	383,947	239,244	-54,541	0.00	925,050
WES 30[250kW]	550,000	517,101	159,404	-89,834	0.00	1.14M
System	2.20M	2.46M	814,927	-224,633	0.00	5.25M

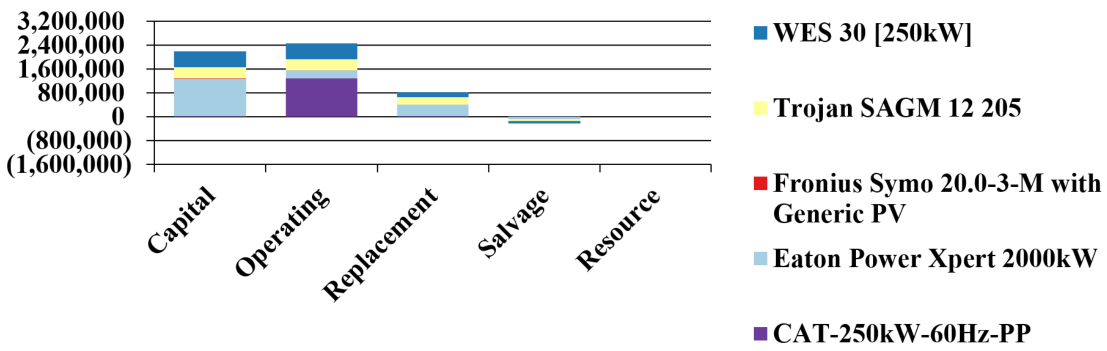

Figure 10. NPC of all the components

A comparison of the basic and proposed energy systems' financial and environmental aspects is provided in Table 12. The base system's NPC is $3.36 million, which is less than the proposed system's $5.25 million NPC. Also, the OPEX (Operation, fuel, and maintenance) costs of the proposed system are less than those of the base system. The suggested approach, however, shows a notable reduction in environmental impact, with fuel consumption falling from 797 liters a year to 360 liters annually and CO_2 emissions falling from 144 kg/yr to 64.4 kg/yr. The suggested system has a higher Capital Expenditures (CAPEX) of $325,800 as opposed to the base system.

According to the comparison of LCOE figures, diesel-based generation costs $0.131 per kWh, whereas the suggested hybrid system costs $0.204. There are several explanations for this disparity. First, compared to diesel generator installations, the initial capital expenditure for renewable energy infrastructure such as solar panels and wind turbines is often higher. In addition, even if fuel costs for renewable energy sources are low, the hybrid system's entire life cycle costs are greatly increased by regular battery replacements and continuous maintenance. Although the proposed system's LCOE is greater as opposed to the base system, the significant environmental benefits point to a potential trade-off that could be acceptable given the objectives of eco-friendly and sustainable energy generation.

The thorough cost assessment over a predicted lifespan of 20–25 years is the basis of the economic study of

Table 12. NPC, CAPEX, OPEX, and LCOE of base system and proposed system

	Base System	Proposed System
NPC	3.36M	5.25M
CAPEX	$73,000	$325,880
OPEX	$254,286	$253,880
LCOE (per kWh)	0.131	0.204
CO_2 Emitted (kg/yr)	144	64.4
Fuel Consumption (L/yr)	797	360

the suggested HRES for Makkovik. The choice of this duration was made to account for the 20–25-year average operating lifecycle of main system components, such as wind turbines and solar panels. Costs during this time were broken down into four categories: replacement costs, possible salvage values after the project, operations and maintenance (O&M) expenses, and initial capital expenditures (CAPEX). It is anticipated that throughout this time, market conditions and technological developments will have a substantial impact on the cost trajectory of renewable energy solutions. Historically, advances in materials science, manufacturing techniques, and economies of scale have caused a steady decrease in the cost of renewable energy components, most notably solar PV modules and wind turbines, as mentioned in studies [41, 42]. We foresee a continuation of this cost drop, making renewable energy more competitive with conventional energy sources, based on industry estimates and historical trends. It is anticipated that over the next ten years, the cost of wind turbines and solar PV will drop by 20–30%, significantly improving the financial sustainability of renewable energy projects. Additionally, advances in battery storage technology might lead to more affordable and efficient energy storage systems, which are essential for controlling the erratic nature of renewable energy sources [43]. The estimated NPC and LCOE estimates are based on these predicted improvements in technology costs and performance, which are essential to the project's economic analysis. Our research offers a more precise and realistic financial picture for the installation of the HRES in Makkovik throughout its anticipated operational lifetime by taking these dynamic cost trends into account."

6.5 Emissions Summary

The hybrid system, integrating diesel with wind and solar, significantly cuts pollution emissions compared to the base diesel system, as shown in Figure 11. This eco-friendly approach to electricity generation notably reduces yearly emissions to 64.4 kg of CO_2, 1.02 kg of CO, with no SO_2, and 6.84 kg of NOx. Whereas, the base system was producing 144 kg of CO_2, 1.02 kg of CO, with no SO_2, and 15.1 kg of NOx. Despite diesel's involvement, its impact is lessened by renewable energy, enhancing efficiency and environmental health.

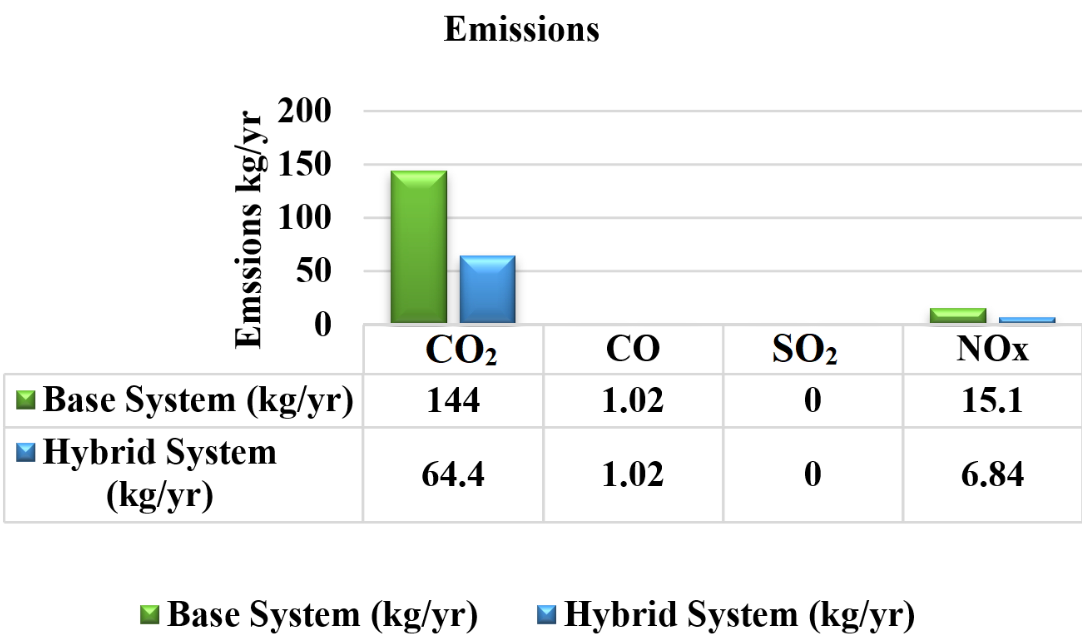

Figure 11. Emission comparison between the base system and the proposed system

6.6 Project Feasibility

The viability and appeal of renewable energy projects are significantly increased in NL by a variety of laws, incentives, and funding channels. The Net Metering Program stands out because it allows users to produce electricity from renewable sources like solar, wind, and hydro, balance their energy usage, and feed any excess energy back into the grid for credits. Through this effort, people and companies may adopt a more financially feasible strategy while also encouraging the growth of renewable technology.

The establishment of the Green Fund strengthens the province's dedication to sustainable energy alternatives. The fund, which is funded by the proceeds from carbon pricing, is devoted to climate change projects, such as renewable energy projects, that try to lower carbon emissions and promote green growth. For initiatives that make a substantial contribution to energy efficiency and environmental sustainability, this financial assistance mechanism is essential.

Numerous subsidies and incentives are offered at the provincial level to help offset the upfront expenses of installing renewable energy systems. These grants provide money for a variety of purposes, such as buying energy-saving equipment or helping with small-scale renewable energy projects and home solar installations, especially in rural and isolated locations.

Federal investment tax credits for clean energy, which support provincial programs and reduce the capital costs associated with such installations, provide substantial incentives for companies investing in conservation and renewable energy systems. To promote innovation and the introduction of fresh, useful technology for renewable energy projects, the province also actively funds and awards research and development in renewable energy technologies.

Notably, the province understands the benefits of working with Indigenous communities in the field of renewable energy. Indigenous-led initiatives are supported by special financial and policy frameworks, highlighting the significance of cooperative, culturally sensitive, and sustainable energy solutions.

6.7 Monte Carlo Analysis

A Monte Carlo analysis was used to take into consideration the uncertainty included in predicting the HRES's economic feasibility. Table 13 is a representation of a Monte Carlo analysis of the project. We can observe how input variability affects the project's financial results thanks to this statistical method. 468 iterations of the simulation were run, illustrating various scenarios that might be impacted by variations in component costs and variations in solar and wind energy supplies.

Table 13. Representation of Monte Carlo analysis

		Cost/NPC ($)	Cost/COE ($)	Cost/Operating cost ($/yr)	Cost/Initial capital ($)
AVG		6,064,342.67	0.26	341,455.36	1,650,173.00
Median		4,762,673.50	0.20	345,159.55	733,000.00
Percentile	10 %	3,124,176.00	0.13	235,670.70	70,300.78
	20 %	3,271,725.00	0.14	236,543.70	77,123.93
MIN		3,119,704.00	0.13	216,280.70	45,000.00
MAX		26,291,110.00	1.13	925,483.70	14,557,620.00

NPC: The NPC is the total discounted value of all project costs throughout the project. The results showed a broad range of results, with an average NPC of $6,064,342.67 and a median of $4,762,673.50. According to the simulation, there is a 10% possibility that the NPC will be as low as $3,124,176.00, which would be a good result in comparison to the average.

COE: The average cost per kilowatt-hour of energy generated by the system is reflected in the COE, which is a crucial indicator of economic viability. The simulation's average COE was $0.26, with observed values ranging from a low of $0.13/kWh to a maximum of $1.13/kWh. This illustrates the possible unpredictability of energy generation costs resulting from undetermined factors.

Operating Costs: $341,455.36 was the average yearly operating cost. This amount includes all recurring costs—maintenance, repair, and labor—needed to keep the energy system operating efficiently.

Initial Capital Investment: $1,650,173.00 was the average initial capital investment determined by the simulation. This is an important number since it shows the upfront costs associated with implementing the system. There is a lot of uncertainty in the range between the lowest ($45,000.00) and highest ($14,557,620.00) estimates, which are mostly determined by market conditions and technological developments.

The results of the Monte Carlo analysis provide us with a probabilistic picture of the project's economic performance and clarify the possible financial hazards. The large variation between the lowest and greatest values highlights how sensitive the project is to different inputs and how crucial risk assessment and strategic planning are.

The present research bolsters the viability of the suggested approach and underscores the necessity of integrating a sturdy risk management structure to alleviate the fiscal risks linked to the project's execution.

6.8 Limitations

Although HOMER Pro offers a strong foundation for technical modeling of hybrid energy systems, it has shortcomings, especially when it comes to modeling dynamic weather and component deterioration over time. Due to these constraints, cautious assumptions on system performance are required, and field data is crucial for fine-tuning and verifying model forecasts.

7 Conclusions

By combining state-of-the-art battery storage and conversion technologies with solar arrays, wind power, and conventional diesel generation, this study offers a revolutionary method of power generation in Makkovik, Newfoundland, and Labrador. Customized to meet Makkovik's unique energy needs, this hybrid system is an outstanding example of advancement in the effort for cleaner energy. In response to the increasing need for sustainable energy solutions, it reduces the community's historical reliance on diesel by utilizing the emission-free generation of solar and wind components. Homer Pro software has been used for the simulation and analysis of this hybrid system. Based on HOMER Pro models, our results show a significant reduction in diesel consumption, paving the way for Makkovik's shift to a more dependable and sustainable energy ecology. In particular, the design of our system dramatically lowers carbon dioxide emissions to 64.4 kg/yr from a baseline of 144 kg/yr, demonstrating our dedication to reducing the effects of climate change. Furthermore, the proposed system's LCOE is $0.204 per kWh, which captures the system's environmental and economic efficiencies while representing all costs incurred over its lifetime. These important results support the feasibility of implementing renewable energy frameworks in isolated communities, supporting local energy security and autonomy while also being in line with global sustainability goals.

The proposition of integrating a HRES in Makkovik is more than a hypothetical exercise; it is a strong cry for a paradigm change in the way isolated, diesel-dependent towns throughout the world view their energy destiny. This research not only demonstrates that renewable energy solutions are feasible in these kinds of environments, but it also shows how Makkovik may evolve into a sustainable development model, providing a path forward for other cities to follow. The study highlights the need for sustainable energy solutions that balance environmental conservation and socioeconomic growth by highlighting Makkovik's possible transition. Makkovik hybrid system can serve as an example of how locally focused and community-driven methods of renewable energy may make a substantial contribution to the global sustainability goals by posing challenges to and eventually changing the current energy dependency. Hence, the proposed transformation of Makkovik transcends both its physical and communal boundaries, serving as a symbol of hope and creativity for isolated communities worldwide. The statement indicates that the use of renewable energy as the foundation for sustainable development is necessary to build resilient, self-sufficient, and environmentally peaceful societies, among the major problems of the twenty-first century.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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