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Hybrid Energy System Design for Enhanced Sustainability in Rigolet, Newfoundland and Labrador

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Abstract: Amid growing concerns over global climate change and the need for sustainable infrastructure development, remote communities such as Rigolet in Newfoundland and Labrador (NL), which primarily rely on diesel generators, face unique challenges and opportunities. This study proposes a transition to a hybrid energy system (HES) that integrates wind and solar energy with battery storage and diesel generator backups. The feasibility and implications of this transformation in Rigolet were assessed using HOMER Pro software, contrasting it with the current diesel-centric model. The feasibility, environmental impact, and economic implications of implementing a HES in Rigolet were thoroughly examined. The methodology employed includes a detailed simulation and optimization of the HES configuration suitable for 125 households with a population of 327. The findings reveal that integrating wind and solar electricity with the existing diesel infrastructure, coupled with battery storage, reduced diesel consumption by 352 tons per year and Carbon Dioxide (CO_2) emissions by 929 tons per year. Additionally, other pollutants such as Carbon Monoxide (CO), Particulate Matter (PM), Sulfur Dioxide (SO_2), and Nitrogen Oxide (NO) were significantly reduced. The proposed system demonstrates a reasonable Net Present Cost (NPC) of \$5.17 million with a Levelized Cost of Energy (LCoE) of \$0.22/kWh. This shift towards a HES not only illustrates significant environmental advantages and an increase in the percentage of renewable energy but also provides economic benefits through cost reductions over the long term compared to the existing diesel-dependent configuration. The proposed system provides a reliable and sustainable energy solution for Rigolet, presenting a replicable and innovative model for other similar remote locations aiming for a greener future.

Keywords: Hybrid energy system; HOMER Pro; Wind energy; Solar energy; Diesel generator; Rigolet; Newfoundland and Labrador; Canada

1. Introduction

Climate change is one of the most pressing anthropogenic issues of the 21st century, with significant implications for ecosystems, societies, and economies throughout the world. The scientific consensus emphasizes the vital need for a rapid transition towards sustainable and resilient infrastructure, particularly in the energy sector, to avoid the detrimental effects of climate change (Jefferson, 2008; Ofélia de Queiroz et al., 2024). Furthermore, the recent escalation of conflict and geopolitical strife in regions like Russia, Ukraine and other European countries has highlighted the risk of dependency on imported fossil fuels. This crisis has served as a catalyst for change, turning nations toward achieving energy security with a diverse energy portfolio (LaBelle, 2023). Remote communities, often reliant on fossil fuels, are particularly vulnerable to the negative effects of such changes and geopolitical energy interruptions. The case of Rigolet exemplifies the difficulties of these remote settlements. The over-reliance on diesel generators not only contributes to greenhouse gas (GHG) emissions but also creates economic vulnerabilities due to fluctuating fuel prices and supply chain uncertainties (Zhao et al., 2023).

HES combines several types of renewable energy sources and storage solutions to create a resilient and transformative solution for off-grid communities. These systems often integrate wind and solar photovoltaic (PV) power sources, leveraging their complementary nature to provide a more consistent and reliable energy supply. The incorporation of battery storage and backup diesel generators further enhances the system's resilience, ensuring energy availability during periods of low wind and solar resources affecting renewable generation. The research has two major objectives: first, to develop and optimize a HES design suitable to the unique climatic and geographical conditions of Rigolet, and second, to evaluate the environmental and economic implications of such a transition, including the prospective cost benefits over the system's lifecycle. By employing the HOMER Pro software, renowned for its capacity to model and optimize off-grid power systems, a comprehensive analysis was provided in this study that contextualizes the technical, environmental and financial advantages of such sustainable development in remote areas. Figure 1 shows the location of Rigolet in NL, extracted from Google Maps.

Figure 1. Location of Rigolet in NL

2. Literature Review

The shift towards sustainable energy systems in distant communities is complex and is influenced by a wide range of technical and economic factors. Rigolet, one of the southernmost Inuit communities in the world, lies on the north coast of Labrador with a population of approximately 327 and 125 households (Government of Canada, 2022). It is the oldest community on Labrador's remote north coast and is located 160km north of Happy Valley-Goose Bay and the entrance of Hamilton Inlet (About Rigolet, 2024). Rigolet is one of NL's twenty detached diesel-generated electrical systems, which are distant from both one another and the provincial electricity grid. NL's sustainable approach for these isolated systems involves a move to renewable energy sources, with additional efforts to encourage Indigenous participation (Government of Newfoundland & Labrador, 2021). To support this transition, the province implemented net metering legislation in 2015, allowing individuals generating up to 100 kW to feed their surplus energy back into the grid, marking a significant step toward sustainable energy practices (Government of Newfoundland & Labrador, 2015).

This literature review section examines the current research relevant to the implementation of off-grid HES in such regions, emphasizing the technical, environmental and economical aspects. Studies, such as those conducted by Karanasios & Parker (2018) and Stringer & Joanis (2023), delve into strategies for decarbonizing Canada's remote microgrids, highlighting the critical necessity of transitioning from diesel generators to HESs.

Karanasios & Parker (2018) included 144 Canadian indigenous communities, highlighting the environmental and socioeconomic issues of diesel generators such as greenhouse gas emissions, spills, leakage, and power outages potentially hindering community development. They adopted a multilevel perspective (MLP) method to examine the diffusion and governance of renewable energy systems (RES) and concluded that those remote indigenous communities are more interested in community-driven, decentralized clean energy systems than technologies promoted by non-aboriginal interests. Stringer & Joanis (2023) took a practical approach by using a cost-based analysis and an optimization model to find the most affordable ways to reduce carbon emissions in off-grid settlements, indicating that wind turbines are the most cost-effective solution for most settlements in 2020, while solar panels are projected to be the most economical by 2050. Communities currently relying on diesel for electricity generation should prioritize immediate decarbonization efforts. In contrast, those using natural gas can wait for their transition until advancements in production and storage technologies become more affordable. Similarly, Kotian et al. (2022) presented a feasible design for a HES, incorporating solar panels, wind turbines, diesel generators, and battery storage to meet the energy demands of Ramea Island, Newfoundland. The use of HOMER software for optimization and MATLAB/Simulink for dynamic simulation demonstrates the technical viability and potential benefits of such a system, resulting in a significant reduction in Ramea Island's reliance on diesel fuel with lower greenhouse gas emissions and energy costs. Kotian & Ghahremanlou (2024) used HOMER Pro software for a comprehensive simulation and design process, supported by geographical insights and existing data on Nain's energy consumption patterns. The results revealed that a combination of diesel generators, wind turbines, and battery storage technology offers the highest reliability, with the lowest NPC of $26.5 million and LCOE of $0.332/kWh. The economic benefits of HESs were highlighted, along with their potential to significantly reduce dependence on diesel generators and the associated environmental impacts.

Additional studies have explored the optimization and design of HES in diverse contexts. For instance, focusing on Baluchistan's coastline, with an average energy demand of 164.55 kWh/day, Khalil et al. (2021) utilized wind and solar energy, with the grid serving as a backup. With objectives centered around minimizing NPC and emissions, the study reveals over 50% emission reductions and notable operational cost savings, thereby promoting sustainability.

Similarly, Yasin & Alsayed (2020) used HOMER Pro to estimate and validate the most efficient system configuration for a small Palestinian community, addressing both residential and agricultural electrical needs. The HOMER Pro software identified a PV-diesel-battery setup as the most economical and environmentally friendly solution to meet the community's energy demand of 349 kWh/day. The results showed that the system had an NPC of $636,150 and an LCOE of 0.438/kWh, highlighting the community's excellent solar resources.

Budes et al. (2020) aimed to reduce the heavy reliance on thermoelectric plants in Colombia's Caribbean region by implementing a HES that combines solar, wind, and battery storage in parallel with the grid. A three-step methodology was adopted. After identifying locations with fragile electricity systems, suitable sites with excellent solar and wind resources nearby were pinpointed. Then HOMER Pro was used to evaluate whether a thermoelectric plant or an HES would be more effective. The system size was optimized for the latter case. The study found that in Puerto Bolivar, the thermoelectric plant remained the more economical option. However, in Rancho Grande, an HES with an optimal configuration of 441 PV arrays and three wind turbines proved more advantageous, with a NPC of $11.8 million and a reduction in CO_2 emissions of 244.1 tons per year.

Considering the wide adoption of HOMER Pro software, Ram et al. (2022) critically examined its various capabilities in performing technical, financial, and environmental assessments of HESs. The authors highlighted simulation, optimization and sensitivity analysis as the core competencies of HOMER Pro while noting its limitations in thermal analysis of energy components and systems.

Although existing literature offers a strong basis for adopting HES in isolated communities, there is still a gap in studying such system design and implementation in Rigolet, NL. Unlike prior studies, which may apply broader assumptions, local data was used for design and optimization processes through HOMER Pro, ensuring the recommendations are tailored and practical for Rigolet.

3. Methodology

The methodology employed in this study starts with a comprehensive review of existing literature focusing on hybrid systems for remote communities. It progresses through a series of steps encompassing load estimation, data collection, system dimensioning, and the simulation and evaluation of standalone HES configurations. Figure 2 illustrates the methodological framework adopted for this study. The HOMER Pro software was selected as the main tool for system design, simulation, and optimization. It is a micropower optimization model with visual C++ at its core whose main aim is to analyze standalone and grid-connected energy systems (Hoarcă et al., 2023; Kumar, 2016).

This software was selected due to its ability to identify an array of technically viable system configurations on the basis of varying NPC. Within the context of this study, a diesel generator-centric system was analyzed as the baseline model, with a hybrid configuration of wind, solar, battery, and diesel considered as the proposed solution. A techno-economic analysis was carried out with a discount rate of 8% and an inflation rate of 2%. The project lifetime is considered to be 25 years for the simulation. The results from each simulated system configuration were further refined and analyzed using Microsoft Excel and the Python programming language for an accurate comparison and evaluation. The base and proposed systems were compared from technical, financial, and environmental perspectives, leading to a conclusion. Furthermore, to enrich the study with local context, the website of the NL government was extensively used to gather demographic information relevant to the research area.

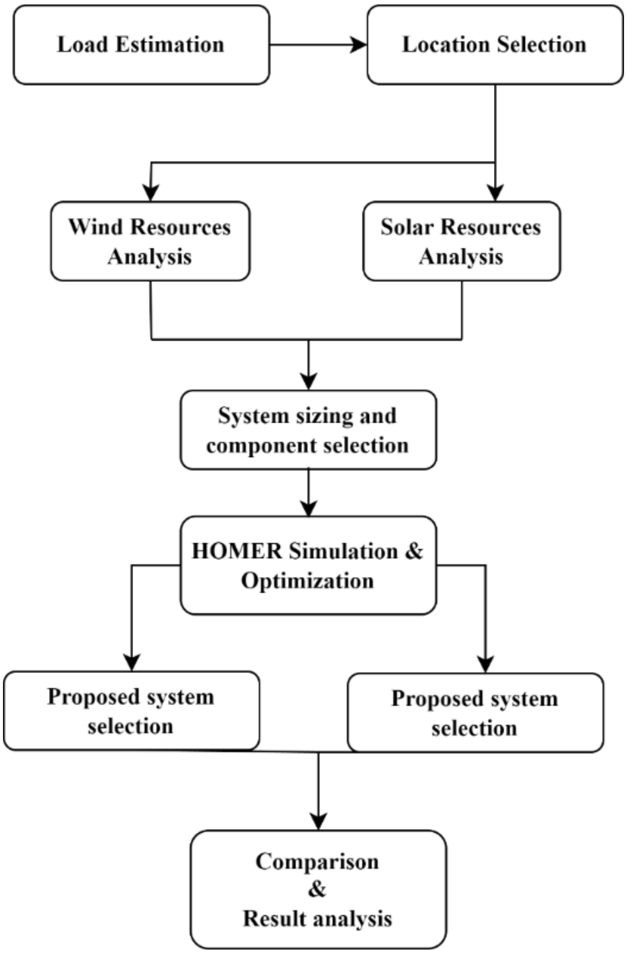

Figure 2. Flowchart of the proposed methodology

3.1 Load Profile

Understanding the energy consumption pattern and load profile of a community is crucial to approximate a reliable system component. It helps to avoid oversizing the system, resulting in unnecessary capital expenditure, and ensures the energy requirements are adequately met. The primary data for the energy consumption pattern of Rigolet was obtained by recalibrating load profiles from demographically similar communities. Specifically, the data from the remote community of Nain, which shares similar demographic and climatic conditions with Rigolet, was used. The data included hourly load profiles over a year, which were adjusted to reflect Rigolet's housing counts and population, as presented in Figure 3 in the form of a heat map. The daily average load was estimated to be 204.5kW while the peak load was 549.34kW. The heat map illustrates a marked increase in electricity consumption during the winter months, predominantly attributed to the need for space heating. This trend underlines the community's seasonal energy demand dynamics, highlighting the critical role of heating in overall electricity consumption in colder periods.

3.2 Wind and Solar Resources in Rigolet

Different geographical locations have different weather data due to various atmospheric conditions such as air pressure, temperature, wind speed and solar irradiation. HOMER Pro offers a comprehensive library of weather data for different locations based on longitude and latitude values. This software enables users to access and import data directly from the Atmospheric Science Data Center of the National Aeronautics and Space Administration (NASA) for simulation and analysis purposes. The monthly wind speed data can be seen in the column chart in Figure 4, which has an average value of 6.47m/s. Similarly, Figure 5 demonstrates the monthly clarity and solar radiation values for solar energy production in Rigolet. The average global horizontal irradiance is 2.87kWh/m^2/day while the clearness index is 0.48. The wind chart indicates higher wind speeds from winter to early spring, while solar potential increases during the summer months. This pattern demonstrates the complementary nature of wind and solar energy resources, offering balanced energy generation potential throughout the year.

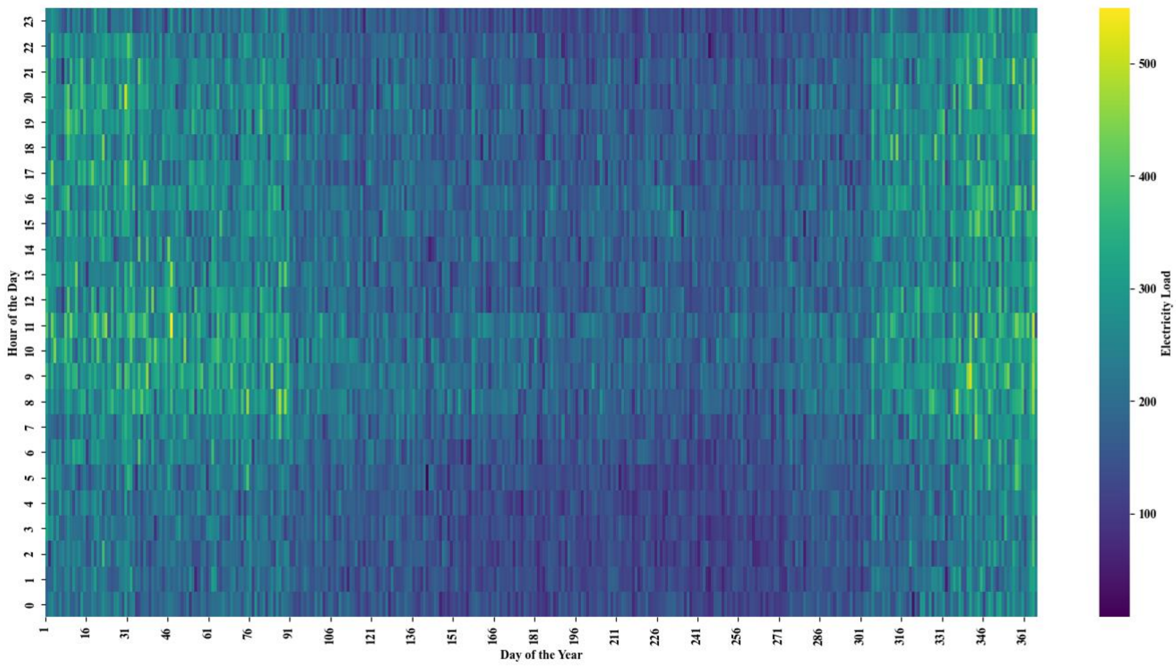

Figure 3. Rigolet's energy demand in the form of a heat map

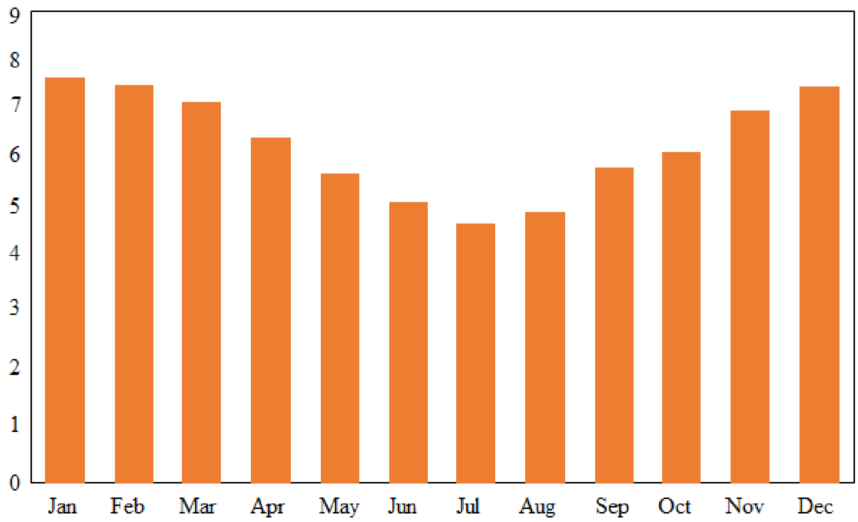

Figure 4. Monthly average wind speed (m/s) of the study location

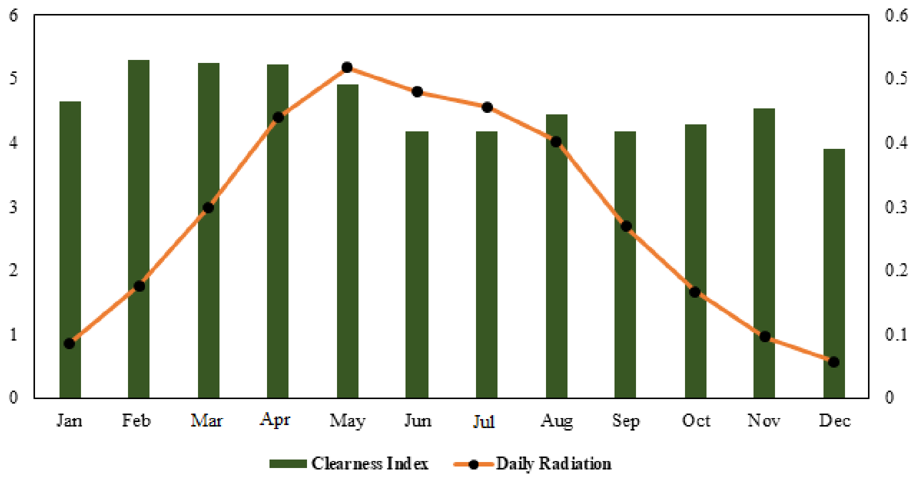

Figure 5. Average monthly solar irradiation and clearness index

3.3 System Sizing and Architecture

HOMER Pro software was used to simulate the optimal system design to satisfy the electricity load of the community. The software is popular for its ability to precisely size the system components and simulate and optimize technical, economical and environmental aspects of the project. Figure 6 represents the layout of the HES, reflecting combinations of generation sources, their energy flow, conversation, storage and dispatch to meet the load. Details of each specific component are listed in Tables 1-5. The system analysis was executed with a discount rate of 8% and an inflation rate of 2%. The project lifetime is considered to be 25 years for the simulation.

Additionally, it was assumed that component operating costs and fuel prices would remain constant throughout the simulation period. This assumption stems from a limitation of the simulation software, which does not support the dynamic changes in these parameters over time. Consequently, this static assumption on costs and prices represents a potential limitation of the study, affecting the long-term economic predictions of the HES.

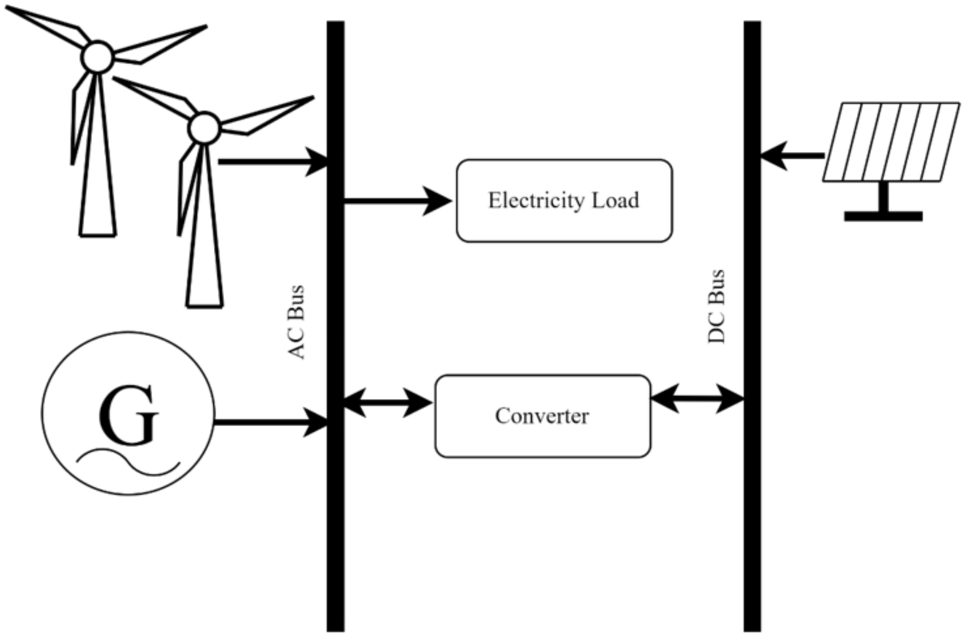

Figure 6. System architecture in HOMER Pro

3.3.1 Wind turbines

Rigolet is known for its consistent wind speeds making it an ideal location to install wind turbines. The system used WES 30 model wind turbines with 250kW energy capacity. These turbines are engineered for efficiency with significant hub height of 48m 30m wide rotors blades to capture higher and wider wind velocity range. The turbine has initial capital cost of $550,000 which includes the cost of transportation and installation. Wind turbines are subjected to various weather condition and might need range of preventive and corrective maintenance to insure its operational reliability (Márquez & Papaelias, 2020). We have allocated operational and maintenance cost of $40,000 to cover scheduled, preventive and breakdown maintenance. Furthermore, $500,000 is secured to replace the damaged parts and components of the wind turbine in the project period. Other technical specifications and financial parameters are listed on Table 1.

Table 1. Techno-economical parameters of WES -30 [250kW] wind turbine (Stehly & Duffy, 2021; Wind Energy Solutions WES, 2024)

Parameter	Values
Name	WES 30 [250kW]
Manufacturer	World Energy Solutions (WES)
Rated capacity	250kW
Capital cost	$550,000
Replacement cost	$500,00
O&M cost	$40,000/year
Hub height	48m
Rotor diameter	30m
Life	>20 years

3.3.2 PV solar panels

In the strategic design of Rigolet's renewable energy portfolio, the integration of solar power plays a pivotal role, facilitated by the selection of the Fronius Symo 20.0-3-M with generic PV panels, each having a capacity of 1 kW. This selection is tailored to harness solar energy efficiently, contributing to the diversification and sustainability of the community's energy sources. The financial blueprint for the solar component involves an initial capital investment of $3,000, a replacement cost of $3,000, and an operational and maintenance cost of $100 per year. Table 2 summarizes the key specifications and financial details of the component.

Table 2. Fronius Symo 20.0.3-M component details (Kotian & Ghahremanlou, 2024; Timalsina & Ghahremanlou, 2024)

Parameter	Values
Name	Fronius Symo 20.0-3-M Generic PV
Manufacturer	Fronius
Rated capacity	20kW
Capital cost	$3,000
Replacement cost	$3,000
O&M cost	$100/year
Life	25 years

3.3.3 Batteries

Within the complex architecture of HES, the integration of energy storage is essential for achieving a harmonized balance between demand and supply. This balance is crucial for ensuring grid stability, particularly in Rigolet's scenarios characterized by the intermittent nature of renewable energy sources. To address these challenges, a strategic selection was made to incorporate the Trojan SAGM 12 205 battery model into the energy mix. This model stands out for its efficient energy storage capacity, defined by a string configuration of 66 units, each with a nominal operating voltage of 12 volts and an energy storage potential of 219 ampere-hours. Table 3 outlays the technical and financial parameters of the battery component in detail.

Table 3. Technical and financial details of battery storage (Kotian & Ghahremanlou, 2024; Timalsina & Ghahremanlou, 2024)

Parameter	Values
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%

3.3.4 Generators

In HESs, where the unreliability of wind and solar power is a concern, the strategic addition of diesel generators, notably the CAT-250 kW and CAT-500 kW-60 Hz-PP types, acts as an important backup to assure uninterrupted electricity supply. This integration was thoroughly assessed not only on operational performance but also on an economic basis, taking into consideration the generator's capital expenditure, replacement, and maintenance expenses per operating hour, as outlined in Table 4. Furthermore, the current diesel price of $1.79 per liter has a considerable impact on operating economics, making fuel cost changes an important concern in total system optimization. This detailed review emphasizes the significance of diesel generators in improving system dependability while also stressing the delicate balance between technical feasibility and economic sustainability in hybrid energy setups.

3.3.5 Converters

The Eaton 2000 model was used in Rigolet's hybrid system design, serving as a bidirectional converter that facilitates the seamless flow of electricity. This specific converter has a power output capacity of 1 kW and a lifespan extending up to fifteen years. The initial acquisition cost stands at $6,000, while the projected cost for replacement after its service life or in case of failure is estimated at $4,500. Additionally, to ensure its optimal performance, an annual maintenance expenditure of approximately $100 is allocated. Table 5 shows the technical and financial specifications of the converter.

Table 4. Technical and financial parameters of generators (Kotian & Ghahremanlou, 2024; Timalsina & Ghahremanlou, 2024)

Parameters	Generator	
Name	CAT-250kW-60Hz-PP	CAT-500kW-60Hz-PP
Capacity	250kw	500kw
Fuel	Diesel	Diesel
Capital cost	$28,000	$45,000
Replacement cost	$20,000	$40,000
O&M cost	$20/hr	$20/hr
Fuel price	$1.79/L	$1.79/L
Minimum load ratio	25%	

Table 5. Technical and financial specifications of the converter (Timalsina & Ghahremanlou, 2024)

Parameter	Values
Name	Eaton Power Xpert 2000kW
Manufacturer	Eaton Power
Rated capacity	20kW
Capital cost	$3,000
Replacement cost	$3,000
O&M cost	$100/year
Life	25 years

4. Results and Discussion

Utilizing HOMER Pro software, an extensive array of potential designs was created for a hybrid system, considering the technical and financial aspects of each component, the wind and solar resources of the location, and most importantly, the design load. HOMER Pro lists out the system configuration that can satisfy the given load in ascending NPC. The combination of CAT-250 and CAT-500 diesel generators was chosen as a base load because this architecture is an existing system in the study location. The technical information, such as electricity generation, fuel consumption, and emissions, along with the financial information, such as NPC and LCoE, was compared with the proposed HES system. Table 6 outlines the selected base and proposed system from HOMER Pro-generated possible arrays.

Table 6. Combination of components from the base and proposed systems (Timalsina & Ghahremanlou, 2024)

Parameters	Base System	Proposed HES	Size	Unit
Generator #1	CAT-250kW-60Hz-PP	CAT-250kW-60Hz-PP	250	kW
Generator #1	CAT-500kW-60Hz-PP		500	kW
Solar PV		Fronius Symo 20.0-3-M	20	kW
Wind turbine	-	WES-30 [250kW]	250	kW
Battery	-	Trojan SAGM 12	9	Strings
Converter	-	Eaton Power Xpert 2000kW	2000	kW

4.1 Electrical Summary

As the primary sources of electricity generation in the base system, the CAT-250kW and CAT-500kW units jointly generated an annual total of 2,216 MWh of electricity. Specifically, the CAT-250kW unit was responsible for 60.54% of this production, while the CAT-500kW unit contributed the remaining 39.46%. This joint production efficiently met the annual power consumption of 2,187 MWh, leaving a little excess of 39 MWh, proving the system's high level of accuracy in meeting demand. In contrast, the new HES proposed in this study produced a total of 3,293.41 MWh of power per year, exceeding the production of the base system and meeting the energy requirement. Wind turbines were the primary source of power in the hybrid system, accounting for 2,451.16 MWh, or roughly 75% of total energy production. Solar power, on the other hand, accounted for only 2.14% of total yearly output, indicating less favorable climatic conditions for solar energy collection. The integration of renewable sources was so successful that just one generator, the CAT-250kW, was required, accounting for 23.41% of total power production. This dramatically improved the energy grid's sustainability, allowing it to run primarily on renewable energy. Figure 7 provides a comprehensive monthly breakdown of the system's power generation and the proportionate contributions of each component. The illustration below demonstrates the hybrid approach's efficiency in using renewable resources to meet and exceed energy demands while minimizing dependency on conventional generators.

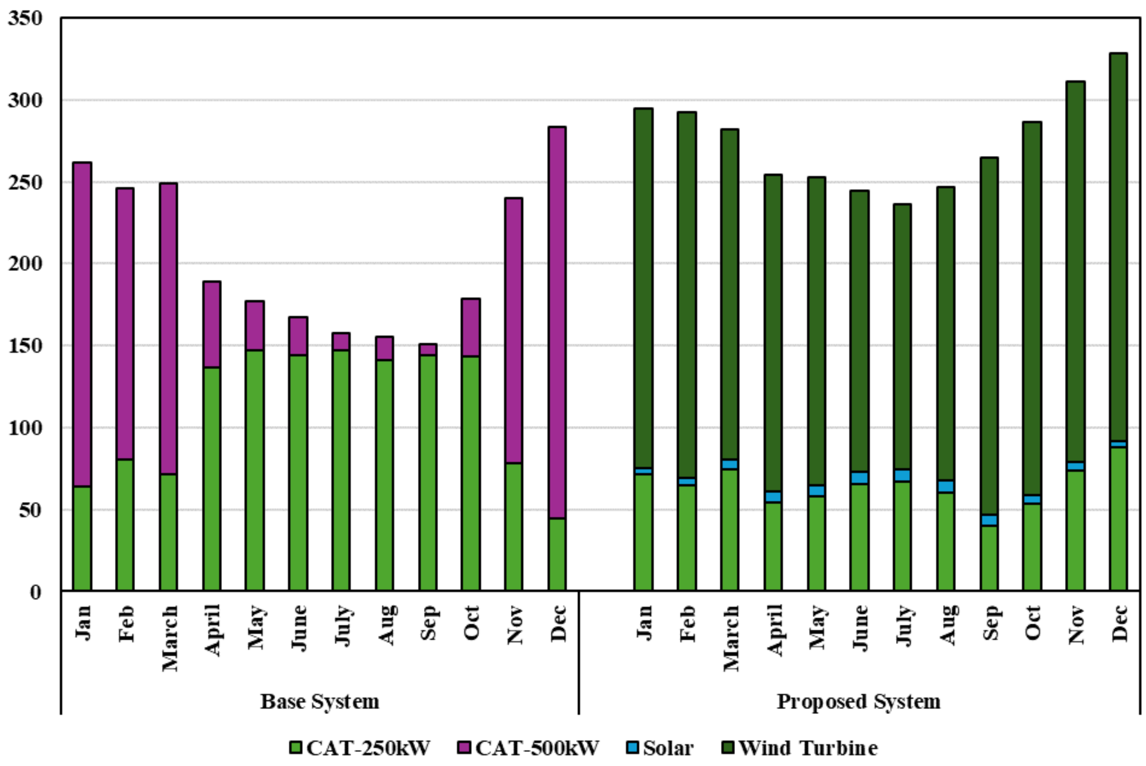

Figure 7. Electricity generation from different sources in different systems

4.2 Fuel and Emission Summary

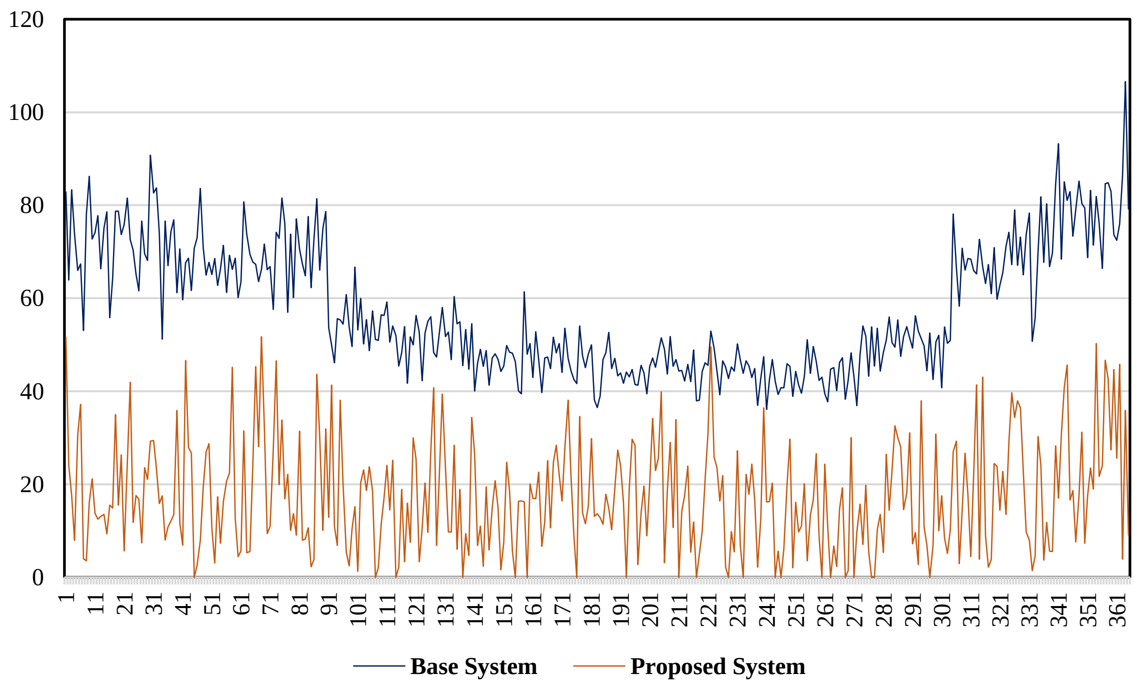

Figure 8. Line graphs to display fuel consumption in each energy system

Figure 8 shows line graphs comparing fuel use across two different energy systems over a period of one year. The conventional system, which relies exclusively on generators, consumes a significant amount of fuel each year, totaling 504.804 tonnes, divided into 1.37 tonnes daily and 0.057 tonnes hourly. In sharp contrast, the use of a HES, which includes wind and solar sources as well as a 250kW generator, results in a large reduction in fuel consumption, saving roughly 352 tons per year, which equates to 0.96 tonnes daily and 0.033 tonnes hourly. The link between pollutants and their emission levels is directly tied to both the type and quantity of fuel consumed. A direct and effective method to reduce emissions in the power sector, as evidenced by this study, involves transitioning to HES as proposed by the study. The traditional diesel-based system exhibits concerning levels of emissions, highlighting the pressing need for alternatives. However, the adoption of HES has proven effective in significantly reducing the levels of CO_2, CO, SO_2, and NO by 930 tonnes, 445 kg, 2.3 tonnes and 6.6 tonnes per year, respectively. Table 7 clearly documents these reductions.

Table 7. Pollutants and their quantification in each system

Quantity	Base System	Proposed System	Reduction	Units
CO_2	1,332,244	403,198	929,046	kg/yr
CO	876	434	442	kg/yr
Unburned hydrocarbons	37.1	16.8	20	kg/yr
PM	44	16.8	27	kg/yr
SO_2	3,306	1,001	2,305	kg/yr
NO	9,539	2,902	6,637	kg/yr

4.3 Cost Summary

Figure 9 presents a detailed financial comparison, showing the NPC for both initial and ongoing expenses, including maintenance and replacement costs for components within the base and proposed systems. The base system's total NPC is $3.12 million, with the majority (about 90%) stemming from operational costs such as fuel and maintenance. In contrast, the proposed HES displays an NPC of $5.17 million, where a large part of the expense is due to the upfront costs for wind turbines, batteries, and converters. The operational costs of the CAT-250kW also contribute significantly to the hybrid system's total cost. This financial analysis is essential for assessing the economic feasibility and sustainability of the project. The NPC for the diesel-based system is lower than the proposed system. However, the proposed system significantly reduces environmental harm by saving 352 tonnes of diesel annually, cutting CO_2 emissions from 929 tonnes/yr. Despite the proposed system's higher energy cost, at $0.22 per kWh compared to the standard system's $0.134 per kWh, its notable environmental benefits suggest it could be a reasonable trade-off for achieving more eco-friendly and sustainable energy production.

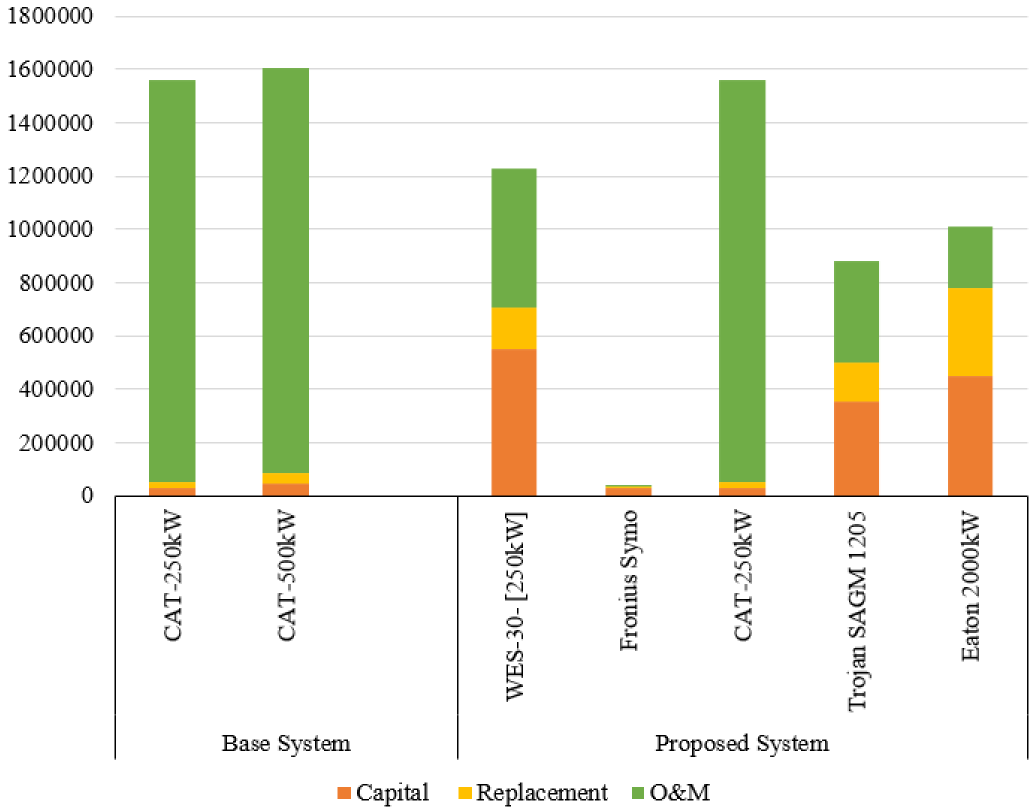

Figure 9. NPC breakdown for each system

5. Conclusion

This study introduces an innovative approach to energy generation in Rigolet, NL, by integrating cutting-edge battery storage and conversion technologies with renewable energy sources such as solar panels and wind turbines, alongside traditional diesel generators. Tailored to address the specific energy requirements of Rigolet, the proposed hybrid system marks a significant leap towards achieving cleaner energy production. It aims to diminish the community's long-standing dependence on diesel fuel by harnessing the power of renewable energy sources, which produce lower emissions compared to diesel centered conventional systems. The analysis and simulation of this system were conducted using the HOMER Pro software, revealing a notable decrease in diesel fuel use. This shift not only supports Rigolet's transition towards a more reliable and sustainable energy infrastructure but also significantly reduces CO_2 emissions by 929 tonnes per year, highlighting the commitment to mitigating climate change impacts. Moreover, the system's LCOE stands at $0.22 per kWh, reflecting both its environmental benefits and economic viability over its operational life. These findings underscore the potential for RES to foster energy independence and sustainability in remote communities, aligning with broader environmental objectives.

6. Policy and Practical Application Recommendations

The transition to a HES aligns well with NL's Renewable Energy Plan. Several key recommendations were proposed for practical implementation. First, it is crucial to integrate the HES within existing provincial frameworks to benefit from available incentives and subsidies. Second, active community engagement should be ensured, with training programs established to enable local communities to effectively manage and maintain the HES. Third, advocating for financial mechanisms such as grants and low-interest loans can help offset the initial capital costs, making the transition economically feasible. Additionally, it is important to assess the local market for renewable energy components to ensure competitive pricing and availability. Finally, it is essential to address potential logistical challenges in transporting and installing renewable energy infrastructure in remote locations. Developing contingency plans for maintenance and fuel supply disruptions will further support the sustainable operation of the HES.

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Data Availability

The data used to support the research findings are available from the corresponding author upon request.

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Conflicts of Interest

The authors declare no conflict of interest.

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