Journal of Green Economy and Low-Carbon Development
https://www.acadlore.com/journals/JGELCD

Optimizing Hybrid Energy Solutions for Enhanced Energy Resilience and Sustainability in Repulse Bay Using HOMER Pro

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Received: 04-15-2024 **Revised:** 06-14-2024 **Accepted:** 06-21-2024

Citation: A. A. Vajari, S. Kotian, S. Shirinnezhad, and D. Ghahremanlou, "Optimizing hybrid energy solutions for enhanced energy resilience and sustainability in Repulse Bay using HOMER Pro," *J. Green Econ. Low-Carbon Dev.*, vol. 3, no. 2, pp. 69–81, 2024. https://doi.org/10.56578/jgelcd030202.

Abstract: This study focuses on enhancing energy resilience in Repulse Bay, a remote community in Nunavut, facing significant power challenges due to the reliance on aging diesel generators. To address these issues, this research explores the development of sustainable hybrid energy systems using HOMER Pro. The optimization results identify a configuration integrating wind turbines and solar panels as the optimal techno-economic solution. The expected outcomes include a substantial reduction in greenhouse gas emissions, increased reliability of energy supply, and significant economic benefits. The proposed hybrid energy system achieves a net present cost of $20.66 million while significantly increasing the renewable energy fraction to 75%. This system drastically reduces greenhouse gas emissions by 60%, aligning with Canada's goal of achieving net-zero emissions by 2050. Additionally, the implementation of this system is projected to create 149 jobs, thus supporting local economic growth. The findings highlight the potential for similar Arctic communities to transition to renewable energy, contributing to global renewable energy efforts. This study not only demonstrates the viability of hybrid energy systems in reducing environmental impact and operational costs but also underscores their broader implications for sustainable development in other remote Arctic regions and beyond. By adopting such systems, Arctic communities can significantly enhance their energy resilience, reduce their carbon footprint, and stimulate economic growth, thereby aligning local initiatives with global sustainability goals.

Keywords: Sustainable development; Microgrid optimization; Renewable energy; HOMER Pro; Repulse Bay

1 Introduction

Canada has committed to achieving net-zero greenhouse gas emissions by 2050, a goal that necessitates transformative changes across all sectors, particularly energy production. This ambitious target drives the need for sustainable and innovative energy solutions that reduce dependency on fossil fuels [1]. One critical aspect of this transition is addressing the energy needs of remote communities, which often rely on outdated and inefficient diesel generators [2, 3].

The Arctic region, characterized by its harsh climatic conditions and isolation, presents unique challenges and opportunities for energy infrastructure development. Energy systems in these areas must be resilient, reliable, and environmentally sustainable to support the well-being and economic growth of local communities [2, 4]. Renewable energy sources, such as wind and solar power, offer promising alternatives to traditional fossil fuels, aligning with global efforts to combat climate change [2].

In Nunavut, the remote community of Repulse Bay exemplifies the energy challenges faced by Arctic regions. Reliant on aging diesel generators, the community endures high operational costs and environmental degradation. Reflecting its expanding population and economic activities, it has faced a 13.2% growth in population between 2016 and 2021 [5]. This increase in population has led to a rising demand for electricity, underscoring the need for sustainable and reliable energy solutions. The integration of renewable energy sources into Repulse Bay's energy system could significantly enhance sustainability, reduce greenhouse gas emissions, and improve energy security [6, 7]. This transformation is crucial for meeting both local energy demands and national environmental objectives [8].

Existing studies have explored the potential of renewable energy in Arctic regions, but there are gaps that necessitate further investigation. For instance, Mustafa and Ashraf [2] and Kamjoo et al. [3] highlight the operational challenges of diesel generators but do not comprehensively address the integration of multiple renewable sources. While, Peddakapu et al. [9] discussed the benefits of wind and solar power, they do not explore their combined effects in hybrid systems tailored for Arctic conditions. Additionally, Owolabi et al. [10] focused on the environmental impacts of diesel dependency without providing detailed economic analyses of renewable alternatives.

This research aims to fill these gaps by investigating the feasibility, sustainability, and economic viability of hybrid energy systems for Repulse Bay, incorporating wind turbines and solar panels alongside existing diesel generators. Utilizing HOMER Pro software, the study models and optimizes various energy system configurations to identify the most effective solutions [11, 12]. The analysis encompasses technical performance, cost-effectiveness, environmental impact, and job creation potential, providing a comprehensive assessment of each scenario [13]. By addressing gaps in existing literature, this research offers a robust framework for policymakers and stakeholders to develop sustainable energy strategies for Repulse Bay and similar Arctic communities [9].

2 Background

Recent advancements in sustainable energy systems have significantly focused on integrating renewable sources such as wind and solar with traditional diesel generators to enhance energy resilience and reduce greenhouse gas emissions [1, 13]. Studies on hybrid configurations have shown promising results across various geographical contexts. For instance, research conducted in Europe and North America has utilized sophisticated modeling tools like HOMER Pro and MATLAB to optimize energy systems, leading to substantial improvements in both economic and environmental performance [4, 14]. These findings underscore the critical need for comprehensive techno-economic analyses to identify the most efficient and cost-effective energy solutions [12, 13]. The unique challenges faced by remote Arctic communities, particularly in Nunavut, have driven targeted investigations into the feasibility and sustainability of hybrid energy systems. Studies focusing on regions similar to Repulse Bay, as well as other remote areas in Canada, emphasize the significant potential of integrating renewable energy sources to meet these communities' specific energy needs [6, 9]. The research highlights the importance of leveraging local renewable resources, especially wind and solar, to shape an optimized energy mix [12]. These hybrid systems not only enhance energy reliability but also contribute to local economic development through job creation and sustainable infrastructure investments [2].

Studies [15–17] provide critical insights into optimizing hybrid energy systems in remote areas. Odetoye et al. [15] present a multi-year techno-economic evaluation of a zero-emission microgrid, illustrating the long-term economic and environmental benefits. Tobaru et al. [16] explore the operation of fuel cells within regional power systems, demonstrating their potential to enhance system reliability. Similarly, Hassan et al. [17] review solar and wind-powered hybrid systems, addressing key challenges and policy implications crucial for advancing renewable energy integration. Complementing these studies, Elazab et al. [18] offer a review of sustainable microgrid models and energy management strategies, providing valuable insights into the future of 100% renewable systems. From a broader strategic perspective, Uddin et al. [19] examine the challenges and future trends in microgrid development, while Gielen et al. [20] highlight the pivotal role of renewable energy in global energy transformation, emphasizing its importance for achieving sustainable development goals. Opeyemi [21] contributes to this discourse by discussing the substitution of non-renewable energy with renewable alternatives, thereby advancing pathways toward sustainable energy consumption. In parallel, Stringer and Joanis [22] explore the decarbonization of remote Canadian microgrids, underscoring the critical importance of renewable integration for sustainability.

Further exploring practical applications and economic viability, studies [23–29] delve into various aspects of hybrid systems. Vurur [23] investigated the interdependencies between urbanization, renewable energy, financial development, and economic growth, while Sharma et al. [24] conduct an economic evaluation of hybrid systems in rural India using HOMER software. Nebey [25] and Ghaffari and Askarzadeh [26] focused on designing and optimizing hybrid power systems, emphasizing the importance of reliability and renewable energy penetration. Ahmadi et al. [28] propose a multi-approach framework for developing sustainable hybrid systems in remote regions, such as Con Dao Island in Vietnam, highlighting their economic viability. Meanwhile, Hasan et al. [27] and Manas et al. [29] provide techno-economic analyses of off-grid and hybrid microgrids, offering critical insights into their performance and sensitivity. Finally, studies [30–32] expand the scope by examining the broader implications of hybrid renewable energy systems. Agajie et al. [30] review the techno-economic analysis and optimal sizing of these systems, while Farahmand et al. [31] and Sakthi et al. [32] explore Canadian hydrogen supply chains and sustainable hydrogen production, respectively. These studies contribute to a deeper understanding of sustainable energy systems and their potential to support both regional and global energy transitions.

Despite these advancements, there remain significant research gaps, particularly in the comprehensive analysis of energy systems tailored to the specific conditions of remote Arctic communities like Repulse Bay. Existing literature often lacks detailed evaluations of job creation potential, long-term economic impacts, and considerations of community-specific environmental and social factors. This paper aims to address these gaps by providing an in-depth analysis of hybrid energy systems that incorporate wind turbines and solar panels optimized for Repulse Bay's unique climatic and geographical conditions. Utilizing HOMER Pro software, this study evaluates various configurations based on technical performance, economic viability, environmental impact, and job creation potential. Table 1 summarizes the key features and focus areas of referenced studies, underscoring the comprehensive nature of this research and its contribution to addressing existing gaps.

Table 1. Analysis of research on energy systems in Nunavut (Publications Up to June 2024)

No.	Ref.	W	S	D	CF ($)	C ($)	R ($)	O&M ($)	F ($)	S ($)	OC ($)	NPC ($)	COE ($)	RF	FC (m^3)	CO_2 (Kg/y)	CO (Kg/y)	Job (#)	Software
1	[8]	x		x	x	x	x	x	x		x	x		x	x	x	x	x	HOMER Pro
2	[9]		x	x	x			x	x		x	x		x	x	x	x		MATLAB
3	[10]	x	x	x	x	x	x	x	x		x	x	x		x	x	x	x	HOMER Pro
4	[18]		x	x	x	x		x	x		x	x		x	x	x	x		MATLAB
5	[22]	x	x	x	x	x	x	x	x		x	x		x	x	x	x		HOMER Pro
6	[23]			x	x	x		x	x		x	x		x	x	x	x		HOMER Pro
7	[24]	x		x	x	x	x	x	x		x	x	x		x	x	x		MATLAB
8	[27]		x	x	x	x		x	x		x	x	x	x	x	x	x		HOMER Pro
9	[25]	x		x	x	x	x	x	x		x	x		x	x	x	x		MATLAB
10	[29]		x	x	x	x		x	x		x	x	x	x	x	x	x		HOMER Pro
This paper	This paper	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	HOMER Pro

Abbreviations: CF: Cash Flow, C: Capital, R: Replacement, O&M: Operation & Maintenance, F: Fuel, S: Salvage, OC: Operating Cost, NPC: Net Present Cost, COE: Cost of Electricity, RF: Renewable Fraction, FC: Fuel Consumption, CO_2: Carbon Dioxide, CO: Carbon Monoxide, Job: Job Creation.

3 Methodology

This research employs a mixed-methods approach, integrating applied and quantitative methodologies to evaluate the feasibility and sustainability of a microgrid energy system for Repulse Bay. As depicted in Figure 1, precise geographic coordinates of Repulse Bay were determined and inputted into the simulation models. Comprehensive data on local renewable energy resources, including solar irradiance and wind speed, were collected through historical climate records to inform the simulations.

The gathered raw input data encompassed historical load profiles, existing diesel generator specifications, wind speed profiles, wind turbine specifications (capacity, hub height, power curve, costs), temperature, solar irradiation, PV panel specifications, battery specifications, and community location. This data was processed to generate model input data, which included load forecasts, updated diesel generator specifications, wind speed forecasts, temperature forecasts, solar irradiation forecasts, and transportation routing and costs.

Specific energy generation technologies, such as Vestas V47 wind turbines, were selected due to their proven efficiency and suitability for Arctic conditions. Similarly, energy storage systems like SAGM 12 205 batteries were chosen for their reliability and performance in harsh climates. The rationale for using these specific technologies is based on their ability to provide stable and reliable energy in remote and challenging environments. The selection of HOMER Pro for simulation was driven by its robust capabilities in modeling and optimizing hybrid energy systems. HOMER Pro allows for comprehensive analysis of technical performance, cost-effectiveness, and environmental impact, making it an ideal tool for evaluating various energy scenarios.

The search space was defined for new diesel generators, wind turbines, PV panels, and batteries. Necessary converters and inverters were chosen to integrate diverse energy sources into a cohesive microgrid system. A dispatch strategy was developed and implemented to optimize the utilization of various energy sources based on their availability, cost, and demand. Simulation software, notably HOMER Pro, was employed to model different hybrid energy scenarios, and the simulation results were analyzed to assess the technical and economic performance of each scenario.

Finally, various energy systems, both non-renewable and hybrid, were evaluated and compared based on the simulation results. Comprehensive analyses were conducted, considering technical, economic, environmental, social, and sustainability factors. The long-term planning optimization phase focused on identifying the optimal number, size, and timing for renewable energy deployment. The goal was to identify the most sustainable and robust energy system configuration for Repulse Bay. The methodology, as outlined in the accompanying flowchart, ensures a rigorous and systematic approach to determining the optimal energy solution for the community.

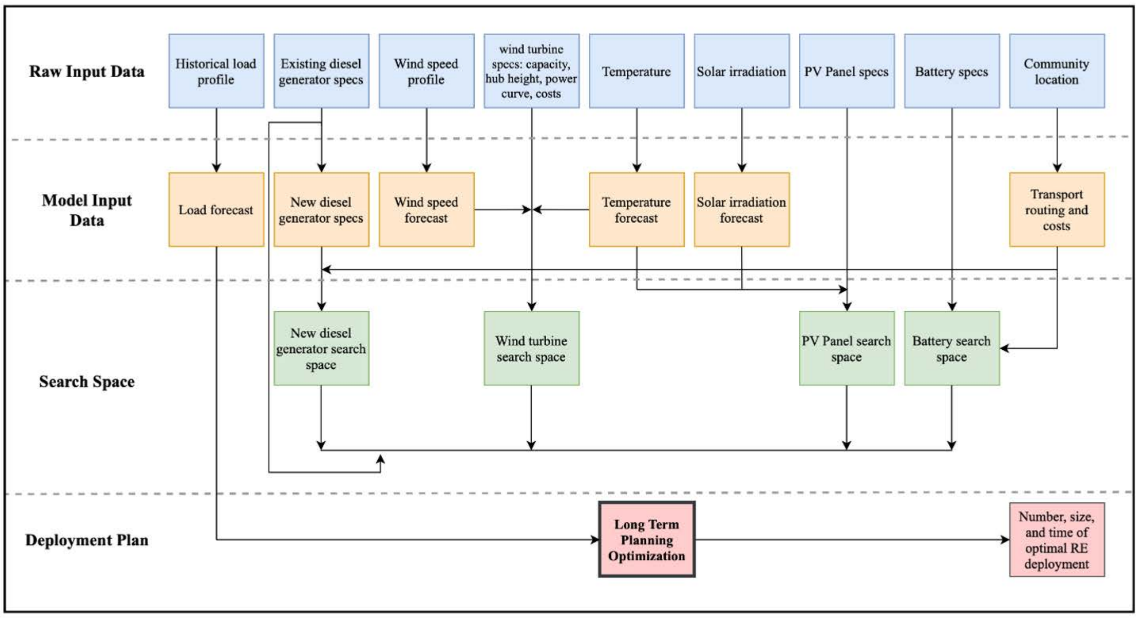

Figure 1. Methodology flowchart

Figure 2. Map showing the position of Repulse Bay, NU

4 Results and Discussion

4.1 Location

Repulse Bay, also known as Naujaat, is situated in the northern region of Canada, within the territory of Nunavut. The geographic coordinates of Repulse Bay are 66.5253° N latitude and 86.2361° W longitude. This location places Repulse Bay within the Arctic Circle, characterized by its extreme climatic conditions, including long, harsh winters and short, cool summers.

Figure 2 illustrates the location of Repulse Bay within the broader context of North America, highlighting its isolation from major urban centres and underscoring the logistical challenges associated with implementing new infrastructure projects. The geographic and climatic data collected from this region are crucial for designing and optimizing a microgrid energy system that is both sustainable and robust, tailored to the unique needs and conditions of this Arctic community.

4.2 Electrical Load Profile

The analysis of renewable energy potential and load profile for Repulse Bay reveals critical insights into the community's energy dynamics. The load profile in Figure 3 data shows a significant variation in energy demand throughout the year, with peak loads occurring during the winter months (January to March and November to December) due to increased heating requirements. Conversely, the summer months (June to August) experience substantially lower demand. This seasonal variation underscores the necessity of designing an energy system capable of handling high winter loads while efficiently managing the reduced summer demand.

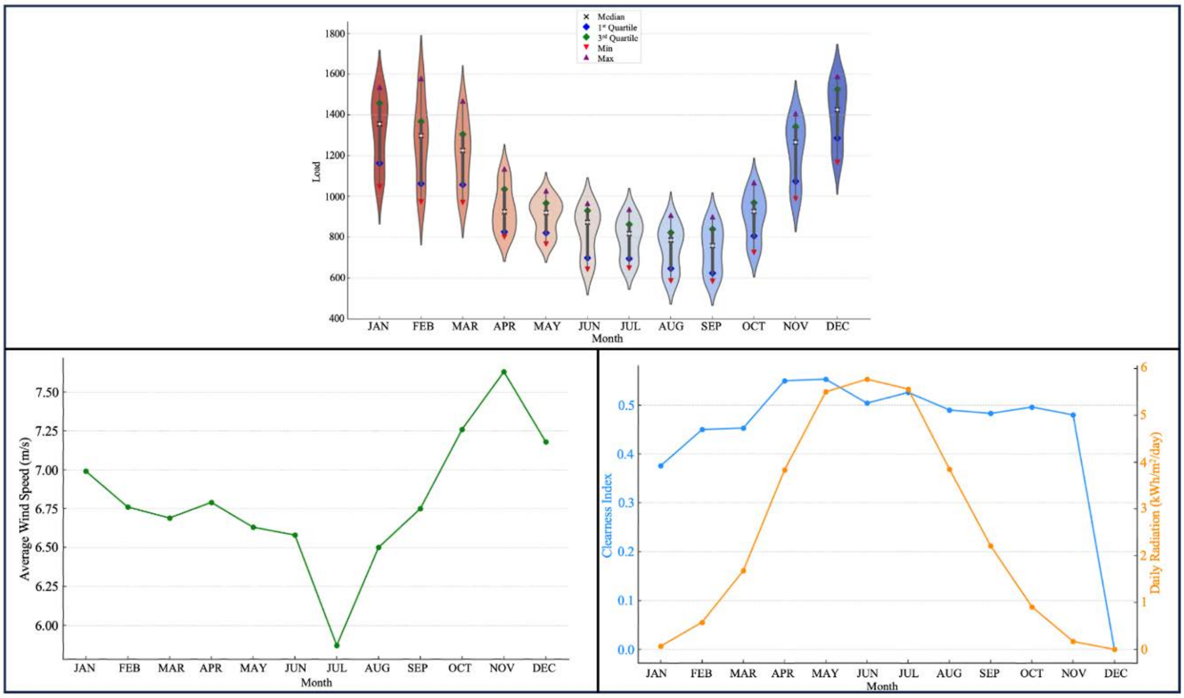

Figure 3. (a) Monthly load profile; (b) Monthly average wind speed; (c) Monthly radiation– Repulse Bay

The wind speed data indicates that wind energy is a viable option for Repulse Bay, particularly during the winter months when wind speeds are highest. The average wind speeds remain relatively stable throughout the year, with a dip in July and August. The highest wind speeds coincide with the peak energy demand in winter, suggesting that wind turbines could significantly contribute to the energy mix, providing reliable power during periods of highest need. This alignment between wind energy potential and load demand is advantageous for the hybrid energy system design.

The solar irradiance data highlights the potential for solar energy during the summer months when daily solar radiation peaks from April to August. This period of high solar radiation overlaps with the lower energy demand, allowing solar panels to offset energy needs during the summer efficiently. A robust and sustainable hybrid energy system can be developed by integrating wind turbines and solar panels with existing diesel generators and incorporating appropriate storage solutions. This system would not only meet the community's year-round energy needs but also reduce dependence on diesel, lower greenhouse gas emissions, and enhance the overall resilience and sustainability of Repulse Bay's energy infrastructure.

4.3 Evaluation of Energy System Scenarios

This section provides a comprehensive analysis of four distinct energy system configurations for Repulse Bay, each featuring different combinations of diesel generators, wind turbines, and solar panels. The goal is to assess the performance, feasibility, and sustainability of these scenarios to optimize the community's energy infrastructure. By examining technical specifications, operational strategies, and potential impacts, this evaluation aims to identify the most effective solution for enhancing energy security, reducing fossil fuel dependency, and promoting sustainable development in this remote Arctic environment.

As depicted in Figure 4, the energy system relies solely on two CAT-1135 diesel generators in Scenario A. These generators are connected to the load via alternating current (AC) circuits, supplying a total power output of 23.5 kW. This configuration represents the current baseline energy system in Repulse Bay, which is heavily dependent on diesel fuel. It includes minimal battery storage, with only one string of SAGM 12 205 batteries, reflecting the limited capacity for energy storage and highlighting the system's vulnerability to diesel supply disruptions.

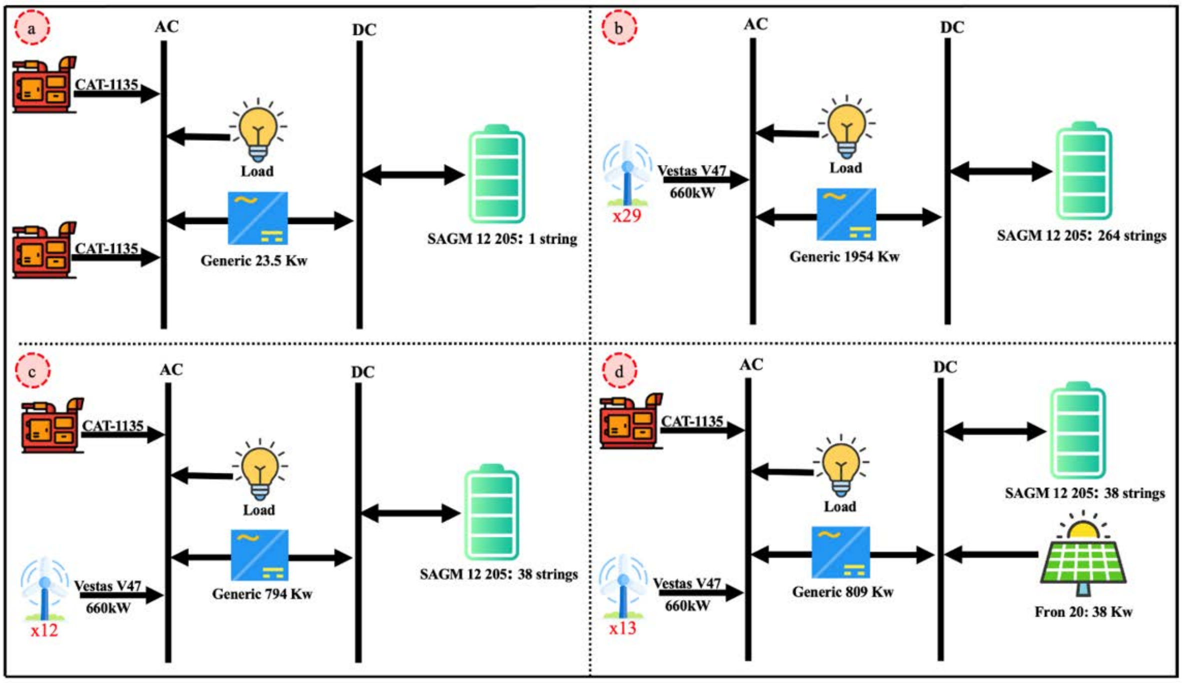

Figure 4. Schematic of the analyzed scenarios using HOMER Pro

Scenario B introduces renewable energy into the mix by integrating 29 Vestas V47 wind turbines, each with a capacity of 660 kW, alongside the existing diesel generators. This hybrid system significantly increases the power output to 1954 kW. The addition of extensive battery storage, with 264 strings of SAGM 12 205 batteries, allows for better energy management and storage of excess wind power. This configuration aims to reduce reliance on diesel fuel, lower greenhouse gas emissions, and enhance energy security.

In Scenario C, the energy system is further diversified by including 12 Vestas V47 wind turbines and a solar component, integrating 20-38 kW Fronius solar panels. This scenario maintains the use of a CAT-1135 diesel generator, providing a hybrid solution that leverages both wind and solar resources. The total power output is 794 kW, with 38 strings of SAGM 12 205 batteries for storage. This diversified approach aims to maximize the use of available renewable resources, providing a more balanced and sustainable energy supply.

Finally, scenario D represents a fully renewable energy system, relying exclusively on 13 Vestas V47 wind turbines, each producing 660 kW, without any diesel generators. The total power output is 809 kW, supported by 38 strings of SAGM 12 205 batteries. This scenario explores the feasibility of transitioning entirely to renewable energy, focusing on sustainability and reducing carbon emissions. The absence of diesel generators highlights the potential for a completely green energy system, though it requires robust battery storage to manage variability in wind energy production.

4.3.1 Technical analysis

In this section, we conduct a comprehensive technical analysis of the four proposed energy system scenarios for Repulse Bay. The objective is to evaluate each scenario's electricity production capacity, efficiency, and ability to meet the community's energy demands. By comparing the total electricity production, excess electricity, unmet electrical load, and capacity shortages, we aim to identify the most effective and sustainable energy solution for Repulse Bay. Figure 5 illustrates the performance metrics for each energy scenario.

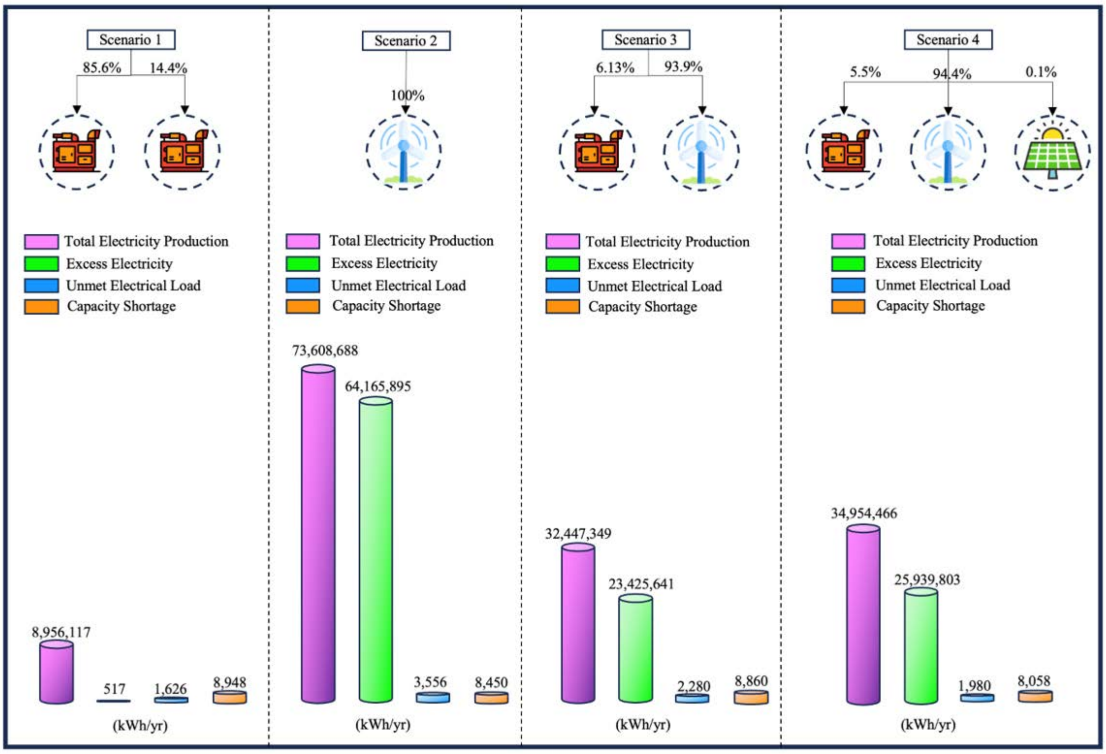

Figure 5. Comparison of annual production across four energy system scenarios

Scenario 1 relies solely on diesel generators, producing a total of 8,956,117 kWh/year. This configuration shows a minor excess electricity production of 517 kWh/year, an unmet electrical load of 1,626 kWh/year, and a capacity shortage of 8,948 kWh/year. The reliance on diesel generators results in limited excess electricity and significant capacity shortages, highlighting the inefficiency and environmental impact of this scenario.

Scenario 2 integrates wind turbines exclusively, with a total electricity production of 73,608,688 kWh/year. This scenario generates substantial excess electricity of 64,165,895 kWh/year, demonstrating a high capacity for renewable energy production. However, despite the large excess, there remains an unmet electrical load of 3,556 kWh/year and a capacity shortage of 8,450 kWh/year. This scenario shows the potential for wind energy but also indicates inefficiencies in balancing production with demand.

Scenario 3 combines diesel generators, wind turbines, and solar panels, producing 32,447,349 kWh/year. This hybrid system results in an excess electricity production of 23,425,641 kWh/year. Despite the diverse energy sources, there is still an unmet electrical load of 2,280 kWh/year and a capacity shortage of 8,860 kWh/year. The integration of solar and wind energy reduces reliance on diesel, but the system requires optimization to minimize unmet loads and capacity shortages.

Scenario 4 focuses on wind turbines supplemented with solar panels, producing 34,954,466 kWh/year. This scenario yields an excess electricity production of 25,939,803 kWh/year. The unmet electrical load is 1,980 kWh/year, and the capacity shortage is 8,058 kWh/year. This configuration demonstrates the highest potential for renewable energy utilization, with the lowest unmet load and capacity shortage among all scenarios, highlighting its efficiency and sustainability.

The comparative analysis of these scenarios underscores the importance of integrating renewable energy sources to enhance system efficiency and sustainability. Scenario 4 emerges as the most promising solution, with the optimal balance of electricity production, minimal unmet load, and reduced capacity shortages. This technical evaluation provides a solid foundation for recommending the most viable energy strategy for Repulse Bay. These findings align with the research objective of developing a sustainable and reliable hybrid energy system for Repulse Bay and highlight the broader context of reducing reliance on diesel generators in remote Arctic communities.

4.3.2 Environmental analysis

The environmental impact of energy systems is a critical factor in evaluating their overall sustainability and feasibility. This section presents an in-depth environmental analysis of the four proposed energy system scenarios for Repulse Bay. The objective is to compare the emissions produced by each scenario, focusing on key pollutants such as carbon dioxide (CO_2), carbon monoxide (CO), unburned hydrocarbons (UHC), particulate matter (PM), sulfur dioxide (SO_2), and nitrogen oxides (NO_x). By quantifying these emissions, we aim to identify the most environmentally friendly solution, contributing to the reduction of the community's carbon footprint and improving air quality. Figure 6 depicts the annual emissions for each of the four energy scenarios.

Figure 6. Emissions comparison across scenarios

Scenario 1 relies solely on diesel generators and produces the highest emissions across all categories. Specifically, it emits 6,955,300 kg/year of CO_2, 7,852 kg/year of CO, 1,318 kg/year of UHC, 1,186 kg/year of PM, 17,275 kg/year of SO_2, and 68,089 kg/year of NO_x. These substantial emissions highlight the significant environmental impact of relying exclusively on diesel generators, underscoring the necessity for cleaner alternatives.

Scenario 2 employs wind turbines exclusively, resulting in zero emissions across all pollutant categories. This scenario demonstrates the potential for completely eliminating harmful emissions through the use of renewable energy sources. It represents the ideal environmental solution, though practical considerations such as energy reliability and economic feasibility must also be addressed.

Scenario 3 combines diesel generators, wind turbines, and solar panels, resulting in significantly lower emissions compared to Scenario 1. This hybrid system emits 1,511,945 kg/year of CO_2, 1,707 kg/year of CO, 286 kg/year of UHC, 258 kg/year of PM, 3,755 kg/year of SO_2, and 14,801 kg/year of NO_x. The integration of renewable energy sources substantially reduces emissions, highlighting the environmental benefits of a mixed energy approach.

Scenario 4 primarily uses wind turbines supplemented with solar panels, with a minimal reliance on diesel generators. This configuration results in emissions of 1,458,409 kg/year of CO_2, 1,647 kg/year of CO, 276 kg/year of UHC, 249 kg/year of PM, 3,622 kg/year of SO_2, and 14,277 kg/year of NO_x. While slightly lower than Scenario 3, these emissions reflect the ongoing, albeit reduced, environmental impact due to the partial reliance on diesel generators.

This environmental analysis demonstrates that Scenarios 3 and 4 offer substantial reductions in emissions compared to the diesel-only approach of Scenario 1, with Scenario 2 presenting the optimal solution in terms of emissions elimination. These insights are crucial for guiding the selection of an energy system that balances environmental sustainability with operational and economic considerations for Repulse Bay.

Furthermore, these findings align with the broader context discussed in the introduction, highlighting the potential for other remote Arctic communities to adopt similar renewable energy solutions to reduce environmental impact and improve air quality.

4.3.3 Economic analysis

This section presents a comprehensive economic analysis of the four proposed energy system scenarios for Repulse Bay. The analysis includes a detailed examination of capital, operating, salvage, and replacement costs, as well as the levelized cost of electricity (LCOE), levelized price of electricity (LPOE), profit margins, and discounted cash flows over a 25-year period. By evaluating these economic metrics, we aim to identify the most cost-effective and financially viable energy solution for the community.

Figure 7 illustrates the capital, operating, salvage, and replacement costs associated with each scenario. Scenario 1, which relies solely on diesel generators, has the lowest total cost of approximately $7.201 million, with operating costs being the dominant factor. Scenario 2, involving wind turbines, has the highest total cost of $53.020 million, primarily due to significant capital and operating expenses. Scenario 3, a hybrid system combining diesel, wind, and solar, incurs a total cost of $21.430 million, while Scenario 4, focusing on wind and solar with minimal diesel backup, costs $20.660 million. These comparisons highlight the high initial investment required for renewable energy systems but also indicate potential long-term savings in operating and replacement costs.

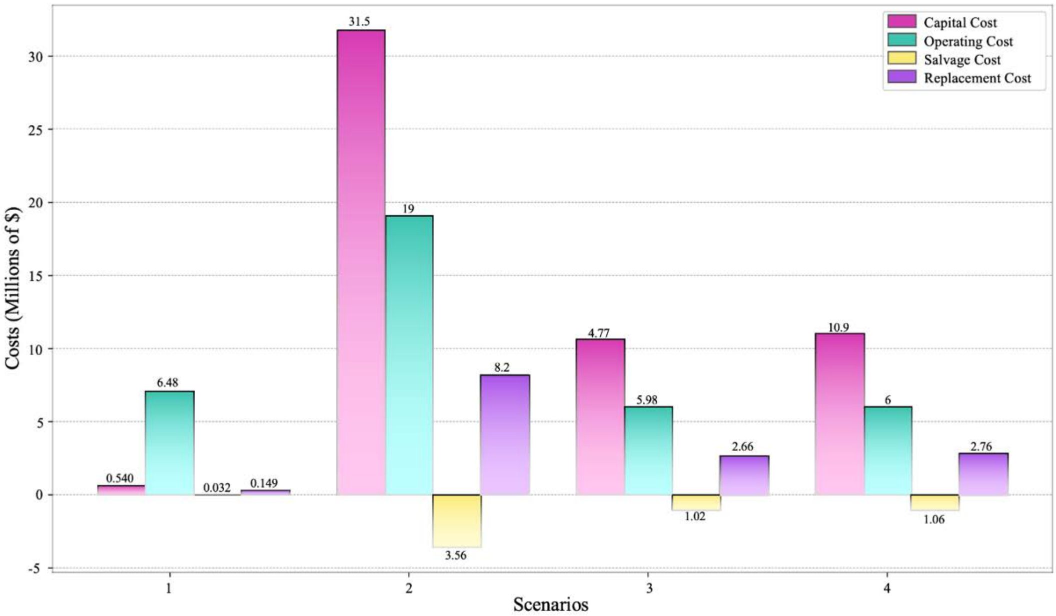

Figure 7. Cost comparison of energy system scenarios

Figure 8 compares the levelized cost of electricity (LCOE), levelized price of electricity (LPOE), and profit margins for each scenario. Scenario 1 has an LCOE of $0.35/kWh and an LPOE of $0.62/kWh, resulting in a profit margin of $0.27/kWh and a total profit of $2.42 million. Scenario 2's LCOE is $0.479/kWh, with an LPOE of $0.62/kWh, yielding a profit margin of $0.141/kWh and a profit of $10.38 million. Scenario 3 achieves the lowest LCOE of $0.219/kWh and an LPOE of $0.62/kWh, producing a profit margin of $0.401/kWh and a profit of $13.01 million. Scenario 4 shows similar financial performance with an LCOE of $0.221/kWh, an LPOE of $0.62/kWh, a profit margin of $0.399/kWh, and a total profit of $13.95 million. These results underscore the financial advantages of hybrid renewable energy systems, particularly Scenarios 3 and 4, which offer the highest profit margins and total profits.

Figure 9 presents the discounted cash flows for each scenario over a 25-year period. Scenario 1 shows a steady cash flow, reflecting the ongoing costs and revenue associated with diesel generation. Scenario 2 displays a significant initial deficit due to high capital costs but achieves positive cash flow by year 3, maintaining steady performance thereafter. Scenarios 3 and 4 demonstrate rapid attainment of positive cash flow within the first year, with consistent performance throughout the analysis period. These cash flow projections highlight the financial sustainability of hybrid renewable systems, emphasizing their ability to provide stable and profitable long-term energy solutions for Repulse Bay.

The most financially viable and sustainable energy system for Repulse Bay can be identified by integrating these economic analyses and balancing initial investments with long-term savings and profitability. These findings have broader implications for other remote Arctic communities, demonstrating that investing in hybrid renewable energy systems can yield substantial economic benefits while enhancing energy security and sustainability. This aligns with the research objective of providing a comprehensive assessment of various energy configurations to inform policy and investment decisions.

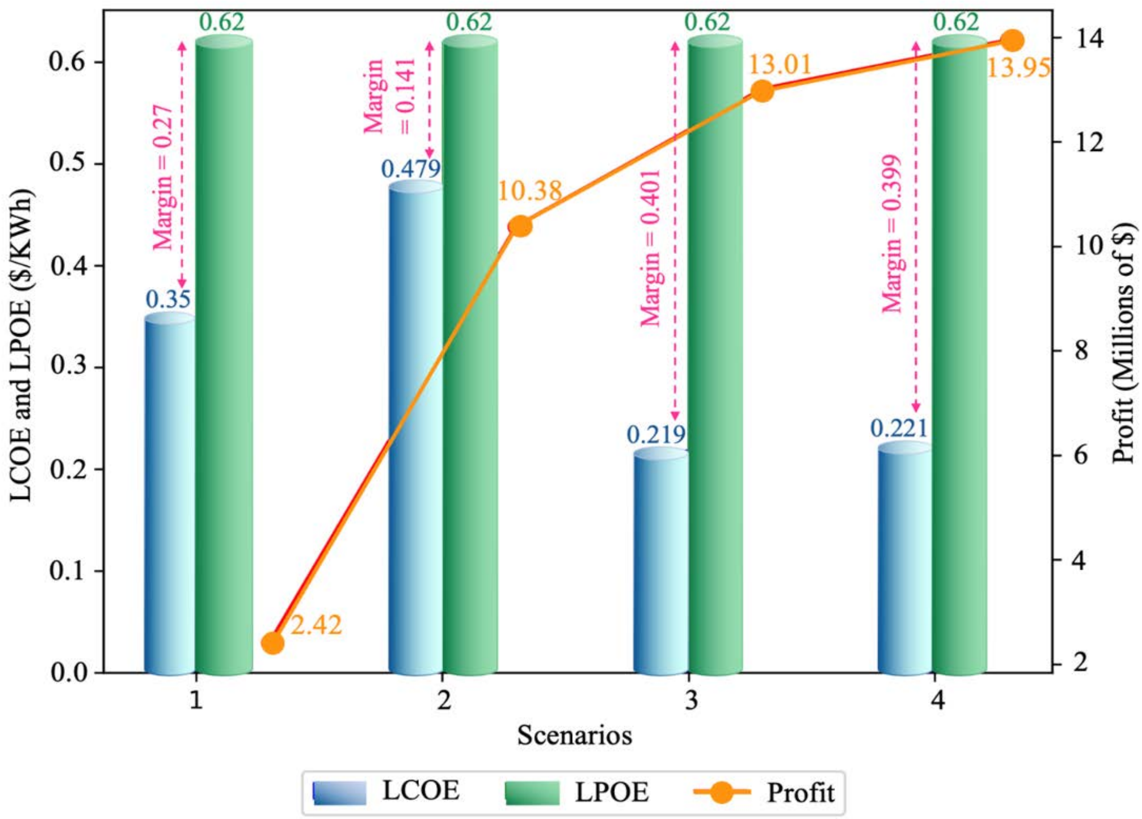

Figure 8. LCOE, LPOE, and profit margins comparison of energy system scenarios

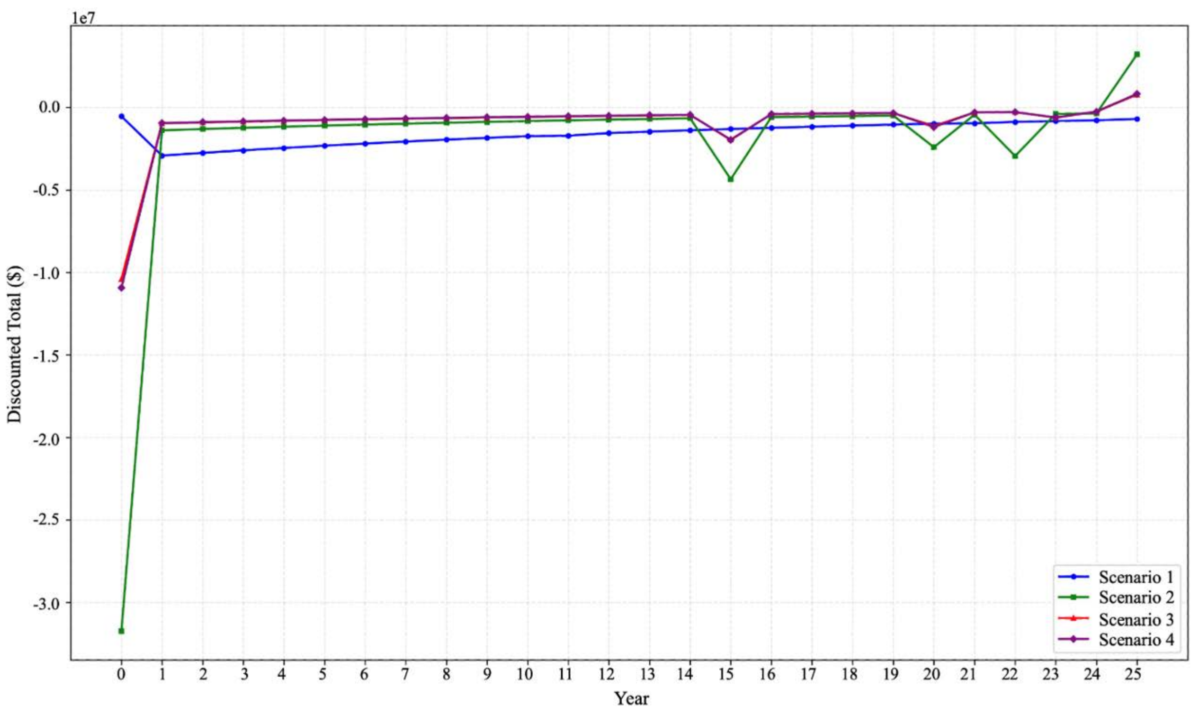

Figure 9. Discounted cash flow analysis of energy system scenarios over 25 years

4.3.4 Social analysis

The analysis of job creation potential across the four proposed energy system scenarios for Repulse Bay reveals significant variations in employment impacts. As Table 2 illustrates, the scenario relying solely on diesel generators results in the creation of 21 jobs during the construction phase and 1 job during the operation phase, totaling 22 jobs. This limited job creation potential is attributable to the straightforward installation and minimal operational requirements of diesel generators.

Table 2. Job creation potential across scenarios

Scenario	Construction Phase Jobs	Operation Phase Jobs	Total Jobs
1	21	1	22
2	290	8	298
3	131	5	136
4	143	6	149

In contrast, the scenario employing wind turbines exclusively demonstrates the highest job creation potential, with 290 jobs generated during the construction phase and 8 during the operation phase, amounting to 298 jobs in total. This substantial employment impact is reflective of the labor-intensive processes involved in wind turbine installation and the ongoing maintenance necessary to ensure their efficient operation.

The hybrid scenario, incorporating diesel generators, wind turbines, and solar panels, yields 131 jobs during construction and 5 during operation, leading to a total of 136 jobs. The diverse energy sources necessitate a broad range of expertise and infrastructure development, resulting in considerable job creation, particularly in the construction phase.

Similarly, the scenario integrating wind and solar power creates 143 jobs during construction and 6 during operation, for a total of 149 jobs. This configuration's high job creation potential is due to the added complexity and coordination required for integrating multiple renewable energy sources, thus fostering substantial employment opportunities.

Comparatively, the wind turbines-only scenario offers the highest job creation potential, driven by the extensive labor demands for both construction and ongoing maintenance. The wind and solar scenario follow closely, reflecting the complexity and continual maintenance needs of a combined renewable system. The hybrid scenario also shows significant job creation, benefiting from the diverse energy sources and their respective infrastructure requirements. The diesel generators-only scenario, with the lowest job creation potential, underscores its limited economic impact in terms of employment compared to the renewable and hybrid alternatives.

This analysis underscores the substantial economic benefits of integrating renewable energy sources into the energy mix for Repulse Bay, not only in terms of sustainability but also in enhancing local employment opportunities. The adoption of renewable and hybrid energy systems promises to create more jobs and foster economic growth within the community, aligning with broader goals of sustainable development and social equity.

These findings highlight the potential for other remote Arctic communities to benefit from similar transitions, demonstrating that hybrid renewable energy systems can significantly contribute to local economic development and social well-being. This discussion ties back to the broader context of the study, emphasizing the transformative impact of sustainable energy solutions on Arctic communities and aligning with global renewable energy efforts.

5 Conclusions

This study assessed the feasibility, sustainability, and economic viability of four energy system scenarios for Repulse Bay, focusing on diesel generators, wind turbines, solar panels, and hybrid combinations. Through detailed technical, environmental, economic, and social analyses, the research identified significant benefits of integrating renewable energy sources into the community's infrastructure. Scenario 4, combining wind turbines and solar panels, was the most promising, offering high efficiency in electricity production, minimal unmet load, reduced capacity shortages, substantial emission reductions, and significant job creation potential. This scenario aligns with sustainable development goals, demonstrating the potential to transform Repulse Bay's energy landscape into a more resilient and environmentally friendly system.

The economic analysis highlighted the financial benefits of renewable and hybrid systems, showing lower operating and replacement costs over time despite higher initial capital expenses, resulting in favorable profit margins and stable cash flows. The integration of renewable energy sources enhances energy security, reduces fossil fuel dependency, and fosters local economic growth through job creation.

The research provides a framework for policymakers and stakeholders to optimize energy solutions for Repulse Bay, paving the way for a sustainable and economically prosperous future. Future research should explore emerging renewable technologies, long-term impacts of hybrid systems, policy enhancements, community engagement, innovative financing models, and comprehensive environmental monitoring. These areas will deepen understanding of hybrid energy systems' potential and challenges in remote Arctic communities, ensuring the benefits of renewable energy are fully realized. Implementing hybrid energy systems could significantly impact long-term community resilience, economic stability, and environmental sustainability, contributing to global climate change efforts and energy equity.

Data Availability

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

Acknowledgment

We gratefully acknowledge the financial backing provided by the Seed Fund (Grant No.: 216737 40500 2000), Faculty of Business Administration, Memorial University of Newfoundland. Furthermore, the authors wish to express their appreciation to Minister Andrew Parsons, Minister of Industry, Energy, and Technology for Newfoundland and Labrador, Canada, for his invaluable inspiration and assistance in promoting renewable energy initiatives. Additionally, our sincere thanks go to Deputy Minister John Cowan for his unwavering dedication and support.

Conflicts of Interest

The authors declare no conflict of interest.

References

[1] H. Farhangi, "The path of the smart grid," *IEEE Power Energy Mag.*, vol. 8, no. 1, pp. 18–28, 2010. https://doi.org/10.1109/MPE.2009.934876

[2] K. M. Mustafa and I. Ashraf, "Evaluation of a hybrid power system based on renewable and energy storage for reliable rural electrification," *Renew. Energy Focus*, vol. 45, pp. 179–191, 2023. https://doi.org/10.1016/j.ref.2023.04.002

[3] A. Kamjoo, A. Maheri, and G. A. Putrus, "Chance-constrained programming using non-Gaussian joint distribution function in the design of standalone hybrid renewable energy systems," *Energy*, vol. 66, pp. 677–688, 2014. https://doi.org/10.1016/j.energy.2014.01.027

[4] T. E. Hoff and R. Perez, "Quantifying PV power output variability," *Sol. Energy*, vol. 84, no. 10, pp. 1782–1793, 2010. https://doi.org/10.1016/j.solener.2010.07.003

[5] Statistics Canada, "Census profile, 2021 census of population," 2021. https://www12.statcan.gc.ca/census-recensement/2021/dp-pd/prof/index.cfm

[6] S. Moser, "Putrajaya: Malaysia's new federal administrative capital," *Cities*, vol. 27, no. 4, pp. 285–297, 2010. https://doi.org/10.1016/j.cities.2009.11.002

[7] K. Ogimi, S. Kamiyama, M. Palmer, A. Yona, T. Senju, and T. Funabashi, "Optimal operation planning of wind farm installed BESS using wind power forecast data of wind turbine generators considering forecast error," *Int. J. Emerg. Electr. Power Syst.*, vol. 14, no. 3, pp. 207–218, 2013. https://doi.org/10.1515/ijeeps-2012-0045

[8] M. M. Kamal, I. Ashraf, and E. Fernandez, "Optimal sizing of standalone rural microgrid for sustainable electrification with renewable energy resources," *Sustain. Cities Soc.*, vol. 88, p. 104298, 2023. https://doi.org/10.1016/j.scs.2022.104298

[9] K. Peddakapu, M. R. Mohamed, M. H. Sulaiman, P. Srinivasarao, A. S. Veerendra, and P. K. Leung, "Performance analysis of distributed power flow controller with ultra-capacitor for regulating the frequency deviations in restructured power system," *J. Energy Storage*, vol. 31, p. 101676, 2020. https://doi.org/10.1016/j.est.2020.101676

[10] A. B. Owolabi, B. E. K. Nsafon, J. W. Roh, D. Suh, and J. S. Huh, "Validating the techno-economic and environmental sustainability of solar PV technology in Nigeria using RETScreen Experts to assess its viability," *Sustain. Energy Technol. Assess.*, vol. 36, p. 100542, 2019. https://doi.org/10.1016/j.seta.2019.100542

[11] S. Kotian, A. Maliat, A. Azeez, and T. Iqbal, "Design and simulation of a hybrid energy system for Ramea Island, Newfoundland," in *2022 IEEE 13th Annual Information Technology, Electronics and Mobile Communication Conference (IEMCON), Vancouver, BC, Canada*, 2022, pp. 589–595. https://doi.org/10.1109/IEMCON56893.2022.9946552

[12] S. Kotian and D. Ghahremanlou, "Design for hybrid power system in Newfoundland and Labrador: A case study for Nain," *Eur. J. Electr. Eng. Comput. Sci.*, vol. 8, no. 1, pp. 1–5, 2024. https://doi.org/10.24018/ejece.2024.8.1.598

[13] S. P. Nathaniel, K. Yalçiner, and F. V. Bekun, "Assessing the environmental sustainability corridor: Linking natural resources, renewable energy, human capital, and ecological footprint in BRICS," *Resour. Policy*, vol. 70, p. 101924, 2021. https://doi.org/10.1016/j.resourpol.2020.101924

[14] A. Naderipour, A. R. Ramtin, A. Abdullah, M. H. Marzbali, S. A. Nowdeh, and H. Kamyab, "Hybrid energy system optimization with battery storage for remote area application considering loss of energy probability and economic analysis," *Energy*, vol. 239, p. 122303, 2022. https://doi.org/10.1016/j.energy.2021.122303

[15] O. A. Odetoye, P. K. Olulope, O. M. Olanrewaju, A. O. Alimi, and O. G. Igbinosa, "Multi-year techno-economic assessment of proposed zero-emission hybrid community microgrid in Nigeria using HOMER," *Heliyon*, vol. 9, no. 9, p. e19189, 2023. https://doi.org/10.1016/j.heliyon.2023.e19189

[16] S. Tobaru, R. Shigenobu, A. Sharma, and T. Senjyu, "Optimal operation method with fuel cells in plural regional power systems," in *2016 IEEE International Conference on Industrial Technology (ICIT), Taipei, Taiwan*, 2016, pp. 442–447. https://doi.org/10.1109/ICIT.2016.7474792

[17] Q. Hassan, S. Algburi, A. Z. Sameen, H. M. Salman, and M. Jaszczur, "A review of hybrid renewable energy systems: Solar and wind-powered solutions: Challenges, opportunities, and policy implications," *Results Eng.*, vol. 20, p. 101621, 2023. https://doi.org/10.1016/J.RINENG.2023.101621

[18] R. Elazab, A. A. Dahab, M. A. Adma, and H. A. Hassan, "Reviewing the frontier: Modeling and energy management strategies for sustainable 100% renewable microgrids," *Discov. Appl. Sci.*, vol. 6, no. 4, pp. 1–19, 2024. https://doi.org/10.1007/s42452-024-05820-6

[19] M. Uddin, H. Mo, D. Dong, S. Elsawah, J. Zhu, and J. M. Guerrero, "Microgrids: A review, outstanding issues, and future trends," *Energy Strategy Rev.*, vol. 49, p. 101127, 2023. https://doi.org/10.1016/J.ESR.2023.101127

[20] D. Gielen, F. Boshell, D. Saygin, M. D. Bazilian, N. Wagner, and R. Gorini, "The role of renewable energy in the global energy transformation," *Energy Strategy Rev.*, vol. 24, pp. 38–50, 2019. https://doi.org/10.1016/j.esr.2019.01.006

[21] B. Opeyemi, "Path to sustainable energy consumption: The possibility of substituting renewable energy for non-renewable energy," *Energy*, vol. 228, p. 120519, 2021. https://doi.org/10.1016/j.energy.2021.120519

[22] T. Stringer and M. Joanis, "Decarbonizing Canada's remote microgrids," *Energy*, vol. 264, p. 126287, 2023. https://doi.org/10.1016/J.ENERGY.2022.126287

[23] N. S. Vurur, "The nexus between urbanization, renewable energy, financial development, and economic growth: Evidence from Turkey," *J. Corp. Gov. Insur. Risk Manag.*, vol. 9, no. 2, pp. 316–326, 2022. https://doi.org/10.56578/JCGIRM090202

[24] K. K. Sharma, A. Gupta, R. Kumar *et al.*, "Economic evaluation of a hybrid renewable energy system (HRES) using hybrid optimization model for electric renewable (HOMER) software—A case study of rural India," *Int. J. Low-Carbon Technol.*, vol. 16, no. 3, pp. 814–821, 2021. https://doi.org/10.1093/IJLCT/CTAB012

[25] A. H. Nebey, "Design of optimal hybrid power system to provide reliable supply to rural areas of Ethiopia using MATLAB and Homer," *Renew.: Wind, Water, Sol.*, vol. 8, no. 1, pp. 1–7, 2021. https://doi.org/10.1186/S40807-021-00067-W

[26] A. Ghaffari and A. Askarzadeh, "Design optimization of a hybrid system subject to reliability level and renewable energy penetration," *Energy*, vol. 193, p. 116754, 2020. https://doi.org/10.1016/J.ENERGY.2019.116754

[27] S. M. N. Hasan, S. Hasan, A. F. Hasan *et al.*, "Techno-economic performance and sensitivity analysis of an off-grid renewable energy-based hybrid system: A case study of Kuakata, Bangladesh," *Energies*, vol. 17, no. 6, p. 1476, 2024. https://doi.org/10.3390/EN17061476

[28] M. M. Ahmadi, H. Hosseinzadeh-Bandbafha, Q. D. Le *et al.*, "A multi-approach framework for developing feasible, viable, and sustainable hybrid energy systems in remote areas: The case of Con Dao Island in Vietnam," *J. Clean. Prod.*, vol. 426, p. 139072, 2023. https://doi.org/10.1016/J.JCLEPRO.2023.139072

[29] M. Manas, S. Sharma, K. S. Reddy, and A. Srivastava, "A critical review on techno-economic analysis of hybrid renewable energy resources-based microgrids," *J. Eng. Appl. Sci.*, vol. 70, p. 148, 2023. https://doi.org/10.1186/s44147-023-00290-w

[30] T. F. Agajie, A. Ali, A. Fopah-Lele, I. Amoussou, B. Khan, C. L. R. Velasco, and E. Tanyi, "A comprehensive review on techno-economic analysis and optimal sizing of hybrid renewable energy sources with energy storage systems," *Energies*, vol. 16, no. 2, p. 642, 2023. https://doi.org/10.3390/EN16020642

[31] F. Farahmand, J. King, D. Ghahremanlou, P. Sakthi, and M. R. M. Jafari, "A comprehensive systematic overview of Canadian hydrogen supply chains downstream," *J. Sustain. Dev.*, vol. 17, no. 2, 2024. https://doi.org/10.5539/jsd.v17n2p1

[32] P. Sakthi, D. Ghahremanlou, and A. B. A. Q. Lardi, "Sustainable hydrogen production, storage, and distribution – A systematic review for Newfoundland and Labrador," *J. Sustain. Dev.*, vol. 17, no. 1, pp. 1–20, 2024. https://doi.org/10.5539/jsd.v17n1p1