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Optimizing Hybrid Energy Systems for Sustainable Development in the Canadian Arctic: A Case Study of Arviat, Nunavut

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Abstract: The optimization of hybrid energy systems for sustainable development in remote Arctic communities is crucial to addressing the unique challenges posed by harsh climates, high energy costs, and the environmental impact of traditional energy sources. This study focuses on Arviat, a community in Nunavut, Canada, and utilizes HOMER Pro software to conduct a comprehensive analysis of combined energy solutions. The economic feasibility, environmental impact, and social benefits of integrating renewable energy sources (RES) with existing diesel systems are evaluated. The findings indicate that, while the initial capital investment required for implementing a hybrid microgrid is significantly higher than that for conventional diesel-only systems, the long-term advantages are substantial. These advantages include increased energy resilience, reduced greenhouse gas (GHG) emissions, lower operational and maintenance costs, and the potential for local job creation. Furthermore, the study highlights that hybrid systems, by reducing dependency on fossil fuels, can provide a more reliable energy supply in regions where logistics for fuel delivery are often hindered by extreme weather conditions. The optimization of hybrid energy systems not only aligns with Canada's net-zero emissions targets but also contributes to the economic and social sustainability of remote communities (RCs) by fostering local energy independence and resilience. This research underscores the transformative potential of adopting hybrid microgrids in isolated Arctic regions, advocating for policies and investments that prioritize sustainable and socially responsible energy strategies in line with national and international environmental goals.

Keywords: Hybrid microgrid; Sustainable development; Energy resilience; HOMER Pro; Arctic communities; Net-Zero emissions; Renewable energy integration; Nunavut

1 Introduction

Approximately 1.1 billion individuals, constituting 14% of the global population, are deprived of access to electricity due to persistent energy supply challenges. Notably, 84% of this population resides in rural areas, with over 95% located in sub-Saharan Africa and the developing regions of Asia [1]. In Canada, approximately 72% of off-grid Indigenous and non-Indigenous communities depend predominantly on fossil fuels for their electricity, with 71% using oil and 0.8% utilizing natural gas. In contrast, only 4.7% of these communities employ RES. Furthermore, 17.9% of the communities meet their energy requirements through interconnections with neighboring communities, while 5.6% rely on unidentified sources of electricity [2].

Supplying electricity to RCs presents significant challenges due to their geographic remoteness, severe weather conditions, distinct consumption patterns, and the limited availability of energy resources. In Canada, access to these RCs is often restricted to seasonal roads, sea routes, or air transport, which complicates fuel supply logistics and necessitates substantial fuel storage for consistent energy delivery. The absence of a connection to the bulk power system prevents these communities from leveraging economies of scale or accessing low-cost power generation. As a result, high operation and maintenance (O&M) costs, coupled with considerable transportation and fuel storage expenses, drive up the overall cost of electricity. Additionally, fluctuations in oil prices can negatively impact the cost of electricity generation in these areas [3].

The Qulliq Energy Corporation (QEC) is the exclusive power utility tasked with the generation and distribution of electricity in Nunavut, catering to approximately 14,400 customers [4]. Nunavut's energy infrastructure is characterized by isolated and unconnected local microgrids, where each community independently manages its electricity generation and distribution. Diesel generators serve as the primary electricity source, with fuel procured and transported in bulk during the brief summer season and then stored in tank facilities for use throughout the extended cold seasons [3].

Energy solutions for RCs must address economic, technical, environmental, and social concerns. From an economic standpoint, solutions must overcome supply and deployment challenges that lead to high energy costs, such as limited transportation access and the inability to share generation and distribution networks among small communities. Technically, energy options need to be evaluated for their suitability under specific operating conditions, often using optimization models to minimize costs. Environmentally, solutions should aim to reduce GHG emissions. Socially, it is essential to understand and meet the diverse acceptability criteria of government bodies, regulators, utility operators, and community members [5].

The significance of this research lies in its comprehensive approach to integrating renewable energy systems into Arviat, aiming to establish a sustainable energy future that aligns with community objectives and environmental stewardship goals. Leveraging HOMER Pro, the study identifies optimal solutions for the proposed hybrid energy system. The transition towards sustainability in Arviat surpasses mere financial and ecological considerations associated with fossil fuel reliance, resonating deeply with societal beliefs and customs. This shift not only aligns with Inuit traditions of preserving land for future generations but also underscores the community's commitment to environmental stewardship. Embracing renewable energy systems offers socioeconomic benefits, including reduced energy costs and environmental impacts, which are crucial for the success of isolated communities. The adoption of hybrid energy systems is expected to stimulate job growth, particularly in construction, maintenance, and system management, providing opportunities for skill development and local employment, thereby enhancing the community's economy.

The paper is structured as follows: The paper begins with a review of relevant literature on energy systems in remote Arctic communities, focusing on the economic feasibility, environmental impacts, and social challenges associated with transitioning to RES. It then details the methodology used, including the application of HOMER software for modeling and simulations, the rationale behind component selection, and the assumptions made during simulations, accompanied by a flowchart illustrating the research process. The design and architecture of the proposed energy configurations for Arviat are presented next, along with an analysis of its electrical load profile and an evaluation of three scenarios. The findings are discussed in terms of technical, economic, environmental, and social aspects, including a sustainability analysis that compares the scenarios. The paper concludes by summarizing the main findings, discussing the potential long-term impacts of hybrid energy systems in remote Arctic communities, and suggesting areas for future research.

This research contributes valuable knowledge and guidance for policymakers, energy planners, and community stakeholders seeking to design and implement sustainable energy solutions in remote areas. By addressing the specific needs and challenges of communities like Arviat, it paves the way for more widespread adoption of renewable energy technologies, ultimately contributing to a more sustainable and resilient energy future.

2 Literature Review

In most remote Arctic communities, electricity grids are isolated and unconnected to regional grids. Typically, these communities have centralized electricity infrastructures, with generation occurring at a few locations within the village. Integrating RES into these infrastructures can transform their electricity generation patterns, shifting towards a more decentralized model and creating micro-grids (MGs). An MG is a well-defined distribution system featuring multiple decentralized and interconnected energy sources and loads that operate as a single controllable unit [6].

Over the past decade, the cost of electricity generated from renewable sources has significantly decreased due to advancements in technology, economies of scale, more competitive supply chains, and the accumulated experience of developers. Consequently, renewable power generation technologies have emerged as the most cost-effective option for new capacity in nearly every region globally. This shift is evident in deployment trends, with renewables comprising 72% of all new capacity additions worldwide in 2019 [7].

Previous research indicates that reducing diesel reliance in several Nunavut communities through the use of municipally scaled renewable electricity is economically feasible. Nevertheless, this transition has not yet occurred, partly due to the challenging social dynamics of electricity generation, which necessitates consensus among a diverse group of stakeholders [8].

However, these studies often do not fully address the social challenges that impede the adoption of renewable energy technologies, particularly in RCs. For instance, the artificially low cost of electricity generated from diesel, limited funding for renewable alternatives, and conflicting priorities among power producers create significant barriers to transitioning to hybrid renewable energy systems [5]. Moreover, while some studies, like those by Cañizares and Das (2019), have conducted thorough investigations into integrating renewable energy into microgrids powered by diesel in Arctic regions, they often lack a comprehensive analysis that includes the social implications and long-term sustainability of such transitions [9].

Arctic communities face widespread unemployment and social challenges, with many jobs being seasonal, part-time, or temporary. This high unemployment rate results in limited tax revenue, which constrains public investment potential. Literature reviews reveal that Arctic communities have restricted financial resources, typically directed toward projects that immediately enhance social well-being, such as repairing aging infrastructure or community buildings like fire stations and first-aid stations. Interviews and case study data suggest that energy infrastructure investment is often deprioritized because its benefits are long-term, while urgent economic and social issues demand immediate attention. Consequently, Arctic communities frequently rely on outdated electricity generators [10].

Achieving energy security requires an optimal mix of primary energy resources. The selection of these resources should adhere to a comprehensive energy policy that considers three essential criteria: environmental sustainability, energy supply security, and cost-effectiveness [6, 10].

Few studies have explored energy systems in Canada's Northern Territories, particularly in the context of comprehensive hybrid systems that integrate multiple RES. Table 1 highlights the energy systems investigated in the Northern Territories until June 2024. The early studies by Jeffries et al. [11] and Arriaga et al. [12] primarily explored the integration of wind and solar power with existing diesel generators in Nunavut (NU) and Arviat, focusing on economic and environmental benefits using tools like Homer Pro and RETScreen. These studies demonstrated potential reductions in fuel consumption and emissions but did not address the full spectrum of RES or conduct in-depth sustainability analyses.

Table 1. Analysis of papers investigating energy systems in Northern Territories (published until June 2024)

		Energy Sources				Economic ($)									Environmental			Social		
No.	Ref.	Diesel	Wind	Solar	CF	C	R	O&M	F	S	OC	NPC	LCOE	RF	FCm^3	CO_2 Kg/y	CO Kg/y	Job #	Software	Location
1	[4]		×			×							×						Homer Pro+ RET Screen	NU
2	[5]	×	×	×		×		×				×							Homer Pro	NU+ Arviat
3	[6]	×	×	×		×			×				×		×	×			Homer Pro+ Matlab	NWT- Sachs Harbour
4	[7]	×	×	×		×	×	×	×	×	×				×	×	×		Homer Pro+ RET Screen	NU-Iqaluit
5	[8]	×	×	×		×			×		×	×				×			Matlab	Arctic
6	[9]	×	×	×		×			×		×		×						Homer+Matlab	Yukon
7	[10]	×	×	×		×		×			×								Homer Pro	NU-Cambridge Bay
This paper		×	×	×		×	×	×	×	×	×	×	×		×	×	×	×	Homer Pro	Arviat

More recent research, such as that by Bahramar et al. [7] and de Witt et al. [13], expanded the scope by including geothermal energy alongside wind and solar in hybrid configurations. These studies, conducted in the Northwest Territories (NWT) and Iqaluit, utilized advanced modeling tools like Matlab and Homer Pro& RETScreen to evaluate economic, environmental, and social impacts. However, they still fell short in incorporating all viable renewable sources. Studies by Garcia-Bernabeu et al. [14] and Vernay et al. [15] further incorporated wind and solar but focused more narrowly on specific locations like the Arctic and Yukon, using Matlab for economic and environmental assessments without a comprehensive evaluation of job creation and social benefits.

This paper fills a critical research gap by optimizing hybrid energy systems for sustainable development in the Canadian Arctic, specifically in Arviat. Unlike previous studies, it includes socioeconomic analysis, thus providing a more holistic analysis. The research employs Homer Pro to conduct a detailed economic, environmental, and social assessment, encompassing parameters such as fuel consumption, CO^2 and CO emissions, cost of electricity, and job creation. By addressing these aspects, this study aims to identify the most sustainable energy system configuration, supporting Canada's dedication to attaining net-zero emissions by 2050 and improving energy sustainability solutions in remote Arctic communities. By focusing on Arviat as a case study, this paper fills a crucial gap in research by providing practical insights into the challenges and opportunities associated with transitioning remote areas from reliance on fossil fuels to RES. This is a gap worth addressing because RCs often face unique energy challenges, including high energy costs, limited access to conventional energy sources, and vulnerability to climate change impacts.

The review is organized into three main themes: (1) the economic feasibility of renewable energy in Arctic regions; (2) the environmental impacts of transitioning from diesel to renewable sources; and (3) social challenges and community engagement in adopting new energy technologies.

3 Methodology

This research utilizes a combination of applied and quantitative research methodologies to accomplish its aim of conducting a preliminary feasibility and sustainability assessment for the establishment of a microgrid energy system in Arviat. This study employs systematic methodology to develop a hybrid energy system tailored for Arviat, Nunavut.

To accurately model the energy systems in HOMER, the geographic coordinates of the project location were entered to ensure precise simulation of local solar and wind resources and climate conditions. The selection of specific components—such as solar panels, wind turbines, and storage solutions—was based on criteria such as efficiency, cost, and compatibility with the local resource profiles. Solar panels and wind turbines were chosen for their proven effectiveness in similar climatic conditions, while diesel generators were considered to ensure reliability, particularly during periods of low renewable energy generation. The decision to integrate additional generation sources like biomass was made to enhance system reliability and provide a diversified energy mix.

The assumptions made during simulations and modeling were explicitly stated and justified within this methodology section. For instance, assumptions regarding fuel costs, maintenance schedules, and equipment lifespan were based on industry standards and insights from previous studies. These assumptions were crucial for ensuring the accuracy and relevance of the simulation results. The capacity, cycle life, efficiency, and cost of the energy storage solutions were also carefully considered to optimize the system's overall performance.

The simulation in HOMER was conducted by developing control strategies to optimize component operations and efficiently meet load demands. The simulation modeled the system's performance over time, considering resource variability, load demand, and component interactions. HOMER's optimization capabilities were utilized to identify the best configuration of components that minimized costs or met other objectives, such as maximizing the use of renewable energy.

Detailed reports generated by HOMER provided comprehensive data on energy production, consumption, storage behavior, and financial performance, allowing for a thorough understanding of system behavior under different scenarios. These reports were analyzed to determine the optimal configuration for the energy system, balancing renewable and hybrid sources.

The study conducted a thorough analysis covering technical, economic, environmental, social, and sustainability aspects of the proposed energy system. Based on these analyses, specific recommendations were provided for the most sustainable energy systems, suggesting technologies, configurations, and strategies that enhance sustainability and align with the community's needs and objectives.

To better illustrate the research process and the sequence of steps involved, a flowchart has been included (depicted in Figure 1). This flowchart visually presents the sequential steps undertaken in the research, from data collection and component selection to simulation and final analysis.

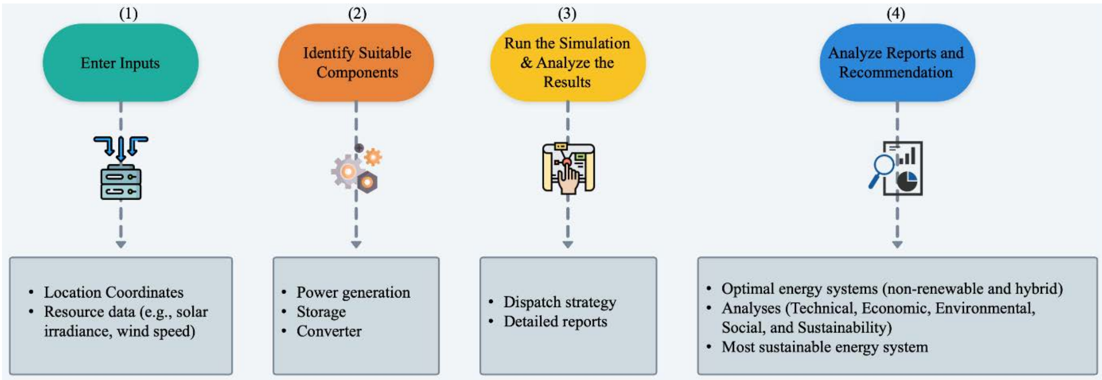

Figure 1. Methodology flowchart

4 System Design and Architecture

4.1 Location

The study location, Arviat, is depicted in Figure 2. Arviat's geographical coordinates are 61°06'30.0" N and -94°03'55.9" W. Arviat is a significant community in the Kivalliq Region of Nunavut, Canada. Reflecting its expanding population and economic activities, it has faced a 7.8% growth in population between 2016 and 2021 (Statistics Canada, 2021). This increase in population has led to a rising demand for electricity, underscoring the need for sustainable and reliable energy solutions.

Figure 2. Map showing the position of Arviat, NU

4.2 Electrical Load Profile of Arviat

Due to the unavailability of public data on the Arviat community's power consumption, the load profile was estimated by scaling the load profile of a similar northern community, considering the number of private households, which is 630, according to Statistics Canada Census, 2021 [16]. This estimated electricity profile, depicted in Figure 3, is based on relevant system components and the specific installation location in Arviat. Arviat's monthly average load exhibits significant seasonal variations. In January, the average load is 3,085.60 kWh/day, reaching a peak of 3,716.911 kWh/day in December. The load decreases during the summer months, with the lowest average of 1,769.89 kWh/day in August. This seasonal variation highlights the importance of effective energy distribution management and accurate system component sizing. The system's scalability and adaptability are strategically designed to meet Arviat's specific energy needs based on these patterns [17].

Arviat's monthly wind speeds were recorded, with December exhibiting the highest speeds at 7.98 m/s, while July had the lowest at 6.19 m/s. This data, derived from global wind speed predictions, is pivotal for optimizing wind turbine efficiency. Additionally, solar radiation and clearness index data for Arviat's in 2023 are presented in in subgraph (c) of Figure 3. June boasted the highest solar radiation, surpassing 5.92 kW/m²/day, while December experienced the lowest, 0.17 kW/m²/day. These findings are indispensable for strategic solar energy planning, shedding light on solar power potential and atmospheric clarity across the year. [St. Brendan+32 St. Brenden's]

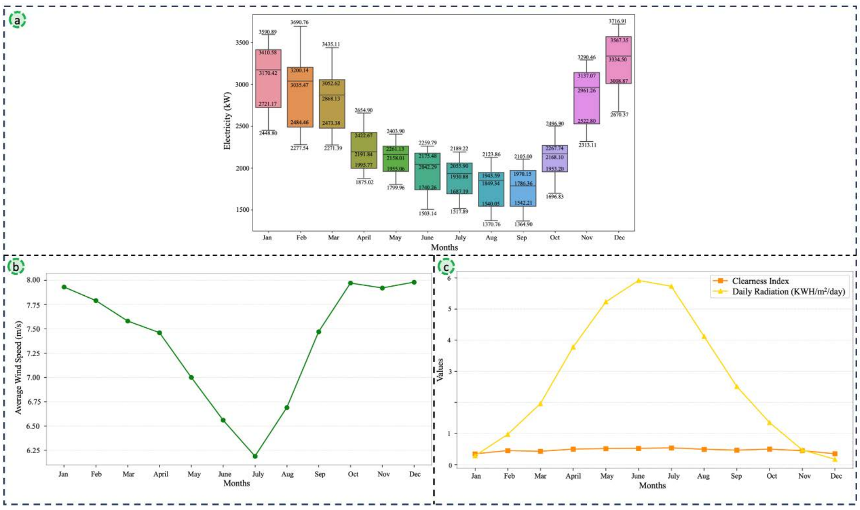

Figure 3. (a) Monthly load profile, (b) Monthly average wind speed, (c) Monthly radiation–rArviat

4.3 Design of the Suggested Configuration

This section presents a thorough analysis of the three distinct scenarios and their components, configuration, and operational strategy to assess their performance and feasibility in addressing the energy needs of Arviat, Nunavut.

In evaluating the energy solutions for Arviat, Nunavut, three scenarios are considered: The first scenario involves a non-renewable system comprising three diesel generators, as illustrated in Figure 4. The system architecture, including the size and capacity of the generators, is outlined in Table 2.

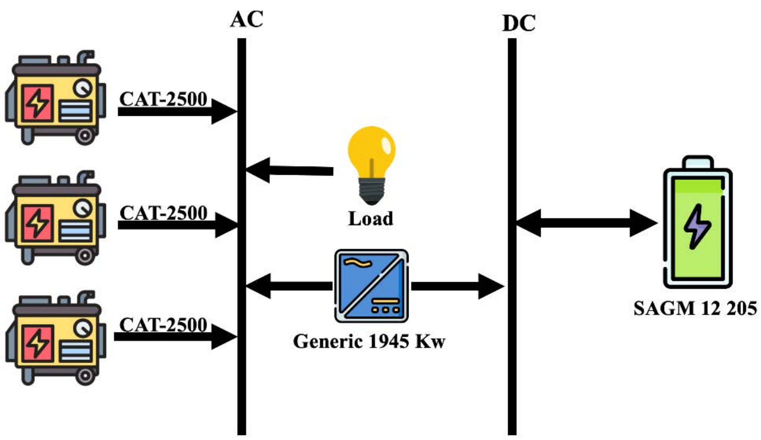

Figure 4. Schematic of the Scenario 1 using HOMER Pro

Table 2. Scenario 1- system architecture

Component	Name	Size	Unit
Diesel Generator	CAT-2500kW-60Hz-CP	2,500	kW
Diesel Generator	CAT-2500kW-60Hz-CP	2,500	kW
Diesel Generator	CAT-2500kW-60Hz-CP	2,500	kW

The second scenario explores a hybrid system that integrates a diesel generator with 33 wind turbines, as depicted in Figure 5. The components of this configuration, including the diesel generator, wind turbines, storage system, and system converter, are detailed in Table 3.

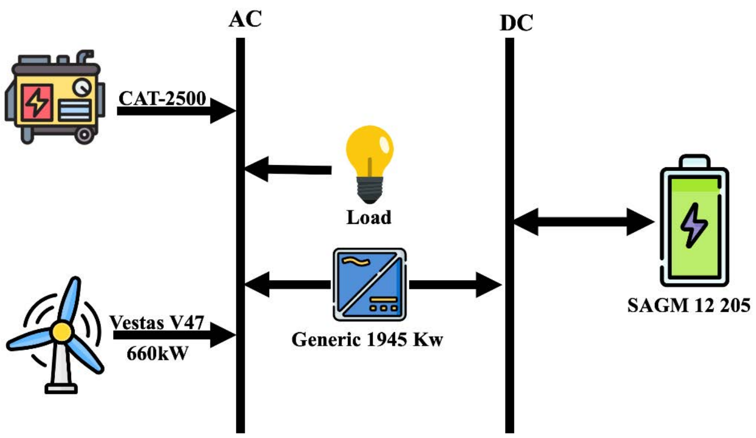

Figure 5. Schematic of the Scenario 2 using HOMER Pro

Table 3. Scenario 2- system architecture

Component	Name	Size	Unit
Diesel Generator	CAT-2500kW-60Hz-CP	2,500	kW
Wind Turbine	Vestas V47 [660kW]	33	ea.
Storage	Trojan SAGM 12 205	98	strings
System Converter	Generic large, free converter	1,945	kW

The third scenario presents a comprehensive hybrid system that incorporates diesel generators, wind turbines, and solar panels, as shown in Figure 6. The architecture of this system, including the solar panels and dedicated PV converter in addition to the other components, is described in Table 4.

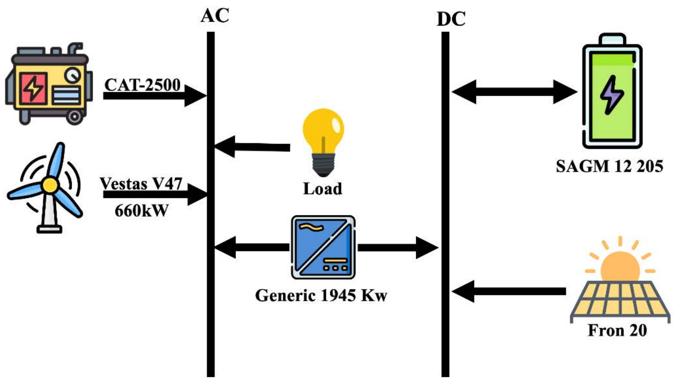

Figure 6. Schematic of the Scenario 3 using HOMER Pro

Table 4. Scenario 3- system architecture

Component	Name	Size	Unit
Diesel Generator	CAT-2500kW-60Hz-CP	2,500	kW
Wind Turbine	Vestas V47 [660kW]	33	ea.
PV or solar panel	Fronius Symo 20.0-3-M with Generic PV	162	kW
Storage	Trojan SAGM 12 205	100	strings
System Converter	Generic large, free converter	1,935	kW
PV dedicated converter	Fron20 converter	20	kW

5 Findings and Analysis

This section presents the outcomes of the System Simulation regarding three different scenarios.

5.1 Technical Analysis

This section offers an evaluative comparison of energy generation and effectiveness across three distinct scenarios for a microgrid energy system in Arviat. Each scenario is assessed in terms of total production, capacity shortage, excess electricity, and unmet electrical load.

Figure 7 depicts that in Scenario 1, the total energy production amounts to 20,942,466 kWh/year. Diesel Generator 1 is the primary contributor, generating 82.42% of the total production, followed by Diesel Generator 2 at 17.19%, and Diesel Generator 3 at 0.38%. This scenario exhibits no capacity shortage or excess electricity, indicating a balanced generation to meet demand. However, there is a minimal unmet electrical load of 956 kWh/year, suggesting a slight shortfall in meeting the total energy demand.

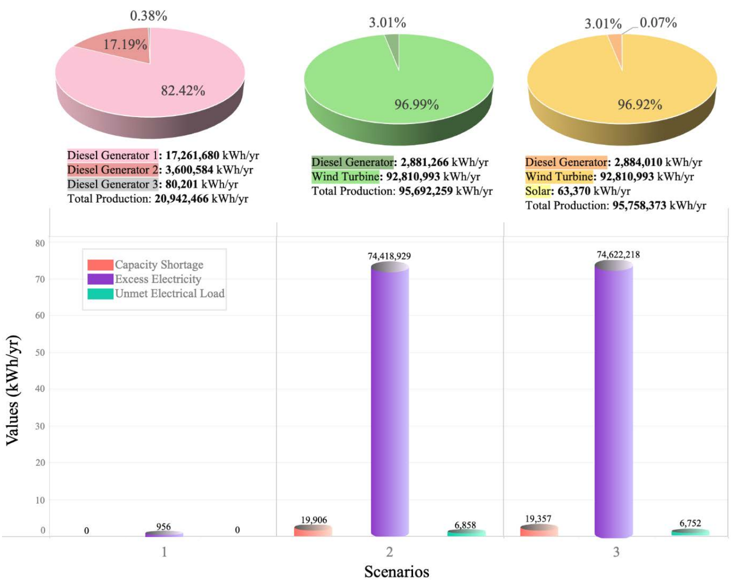

Figure 7. Annual production of each component

Scenario 2 significantly increases the total energy production to 95,692,259 kWh/year. Wind turbines are the dominant source, contributing 96.99% of the total production, while the diesel generator accounts for 3.01%. Despite the increased production, this scenario experiences a capacity shortage of 19,906 kWh/year, indicating some periods of insufficient generation capacity. Additionally, it produces a substantial amount of excess electricity (74,418,929 kWh/year), reflecting potential overproduction during peak wind conditions. The unmet electrical load in this scenario is relatively low at 6,858 kWh/year.

Scenario 3 resulted in a total energy production of 95,758,373 kWh/year. Wind turbines contribute 96.92% of the total production, diesel generators 3.01%, and solar panels 0.07%. Similar to Scenario 2, this scenario faces a capacity shortage of 19,357 kWh/year. It also generates a significant amount of excess electricity (74,622,218 kWh/year), suggesting further opportunities for optimizing energy storage or distribution. The unmet electrical load is slightly lower at 6,752 kWh/year, indicating a marginal improvement in meeting demand compared to Scenario 2.

Hence, Scenarios 2 and 3 dramatically enhance total energy production compared to Scenario 1, primarily due to the integration of wind turbines and, to a lesser extent, solar panels. However, both Scenarios 2 and 3 exhibit capacity shortages and substantial excess electricity, pointing to an over-reliance on intermittent renewable sources. The unmet electrical loads in these scenarios are higher than in Scenario 1 but remain relatively low.

5.2 Economic Analysis

The expenses related to renewable energy equipment have historically raised concerns. However, over recent years, there has been a notable reduction in these costs, rendering renewable energy an economically feasible choice for hybrid systems in select locations [18].

Figure 8 reveals distinct differences in capital, operating, replacement, and salvage costs. Scenario 1, which relies solely on diesel generators, incurs the lowest capital cost at $825,000 but has the highest operating cost of $14.5 million due to substantial fuel consumption and maintenance requirements. Additionally, the replacement cost for this scenario is relatively low at $210,642, and it has a salvage cost of -$100,339, reflecting minimal residual value.

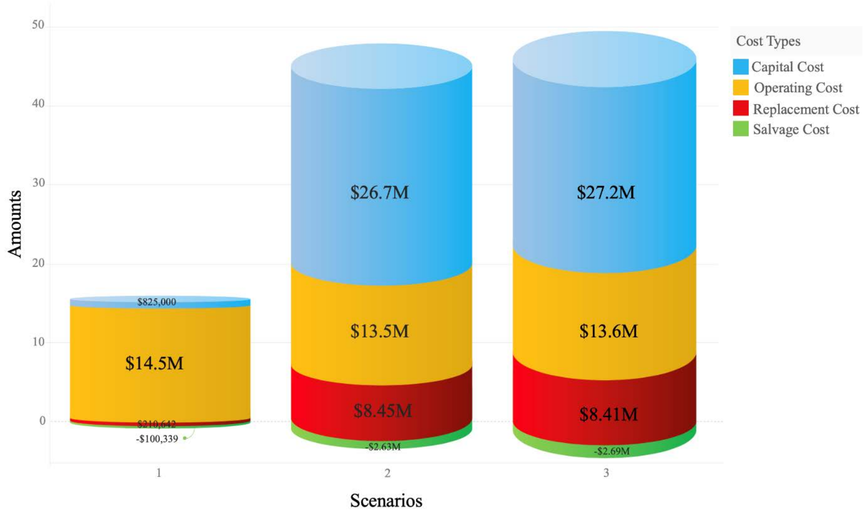

Figure 8. CAPEX, OPEX, REPEX, SALEX of scenarios

In contrast, Scenario 2, which integrates wind turbines with diesel generators, significantly increases the capital cost to $26.7 million, reflecting the investment required for renewable energy infrastructure. However, this scenario benefits from reduced operating costs at $13.5 million, owing to decreased fuel dependency. The replacement cost rises to $8.45 million, indicating higher costs associated with maintaining and replacing wind turbine components. The salvage cost improves to -$2.63 million, indicating a better residual value compared to Scenario 1.

Scenario 3 presents the highest capital cost at $27.2 million. Nevertheless, it achieves the lowest operating cost among the three scenarios at $13.6 million, benefiting from the combined efficiencies of wind and solar energy. The replacement cost is slightly lower than Scenario 2, at $8.41 million, due to the additional longevity and reduced wear on the integrated system components. The salvage cost is -$2.69 million, reflecting the highest residual value among the scenarios.

Overall, while Scenario 3 demands the highest initial investment, it offers the most favorable economic outcomes in terms of operating and replacement costs, as well as residual value, highlighting the long-term financial benefits of incorporating clean sources of energy into the energy infrastructure.

Figure 9 compares three different scenarios, focusing on their total electricity production, Levelized Cost of Electricity (LCOE), Levelized Profit of Electricity (LPOE), margin, and profit. These metrics provide a comprehensive overview of the economic performance and viability of each scenario.

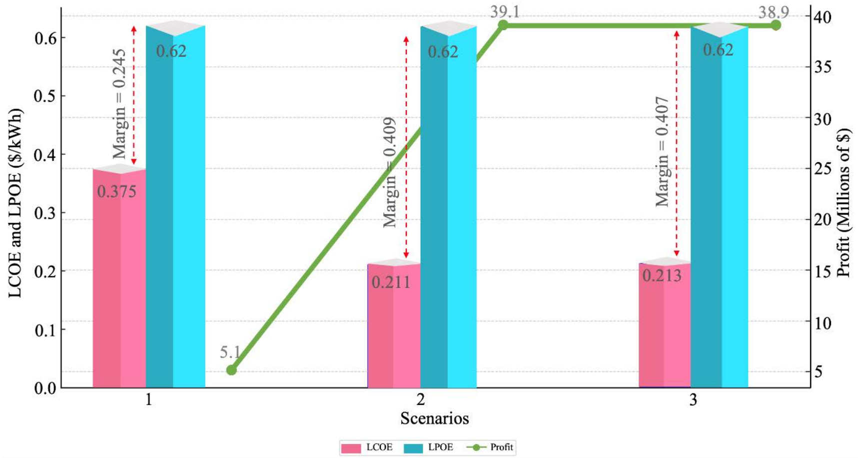

Figure 9. LCOE, LPOE, profit, and margin of scenarios

Despite the simplicity of the first scenario, it shows the highest LCOE, 0.375 $/kWh, indicating higher production costs. Consequently, its margin and profit are significantly lower compared to the other scenarios.

Second Scenario, integrating renewable wind energy with a diesel generator and storage solutions drastically reduces the LCOE to 0.211$/kWh and enhances the margin to $0.409/kWh. The high total electricity production and improved economic efficiency led to a substantial increase in profit.

While the LCOE is slightly higher in Scenario 3 than in Scenario 2, 0.213$/kWh, the overall margin remains competitive at $0.407/kWh. The total electricity production and profit figures are similar to Scenario 2, showing the economic benefits of a diversified energy portfolio.

Figure 10 depicts the discounted total cash flow for three distinct energy production scenarios over the project lifetime, a 25-year period. Scenario 1 maintains the least favorable cash flow trend, with consistently high costs and minimal return, indicating poor economic sustainability.

However, Scenario 2 shows a more favorable cash flow trend, with reduced initial and ongoing costs. This scenario demonstrates improved economic viability and sustainability.

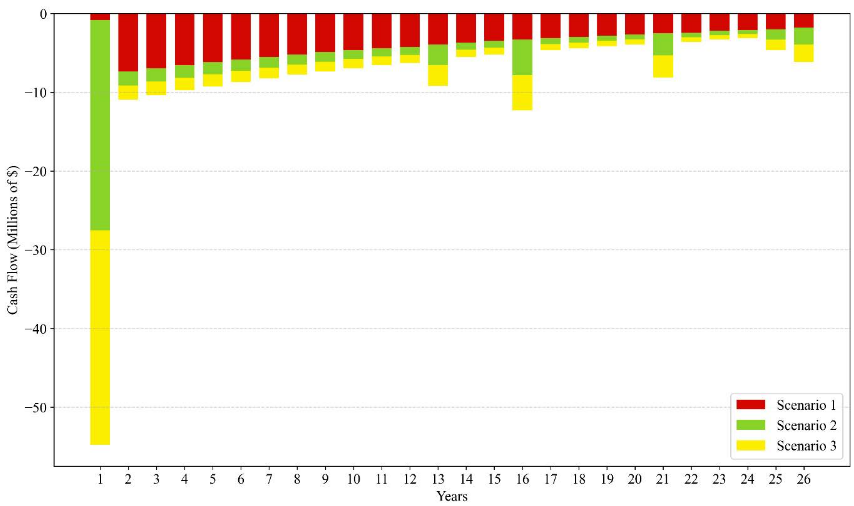

Figure 10. Discounted total cash flow for scenarios

Moreover, Scenario 3 presents a favorable cash flow trend, similar to Scenario 2, but with slightly higher initial costs. The integration of both wind and solar energy helps in maintaining low operational costs, contributing to sustainable financial performance.

5.3 Environmental Analysis

As depicted in Table 5, the fuel analysis delineates the annual diesel consumption for each scenario. Scenario 1 shows a total feedstock consumption of 6,220,217 liters, with an average daily usage of 17,042 liters, translating to 710 liters per hour. Scenario 2 consumes 804,441 liters annually, averaging 2,204 liters per day and 91.8 liters per hour. Scenario 3 has a total consumption of 805,699 liters per year, with an average daily usage of 2,207 liters and 92.0 liters per hour.

Table 5. Fuel summary

Scenario	Total Feedstock Consumed(L)	Avg Feedstock Per Day(L/day)	Avg Feedstock Per Hour(L/hour)
1	6,220,217	17,042	710
2	804,441	2,204	91.8
3	805,699	2,207	92

Scenario 1, relying solely on diesel generators, results in substantial fuel consumption and significant emissions, including high levels of carbon dioxide, carbon monoxide, particulate matter, sulfur dioxide, and nitrogen oxides. Scenario three, adding solar panels to the diesel and wind hybrid system, demonstrates a reduction in fuel consumption and emissions, leveraging wind energy to offset reliance on diesel. The second scenario, which integrates wind turbines with a diesel generator, further enhances environmental benefits by reducing fuel consumption and emissions to the lowest levels among the three scenarios, as shown in Figure 11. This comparison underscores the critical environmental advantages of incorporating RES into the energy infrastructure of RCs like Arviat.

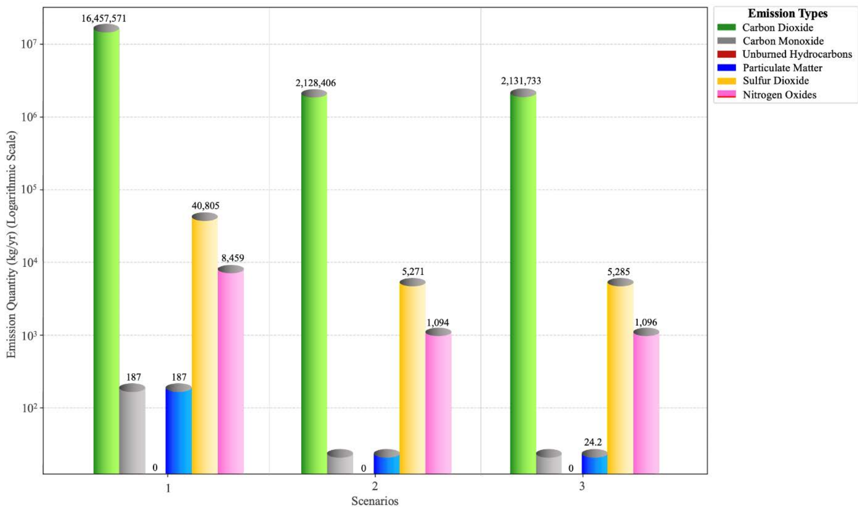

Figure 11. Emission summary

A comparative analysis of emissions from three scenarios for Arviat reveals significant differences in environmental impact. Scenario 2 shows a significant decrease in carbon dioxide emissions, with values falling from 16,457,571 kg per year on the base to 2,128,406 kg per year, which is an astonishing 87% reduction.

The significant reduction in GHG emissions in Scenario 2 aligns with the study's objective of identifying environmentally sustainable energy solutions for Arviat.

5.4 Social Analysis

The comparative analysis of the three energy scenarios reveals significant variations in job creation during both the construction and operations phases. Scenario 1 generates the least number of jobs, with 22 jobs during the construction phase and 2 jobs during the operations phase. This scenario underscores the limited employment potential of conventional non-renewable energy systems, highlighting the need for more diversified energy solutions to enhance job creation in RCs.

In contrast, Scenario 2, substantially increases job creation, with 172 jobs throughout the building phase and 12 jobs during the operations phase. The dominance of wind energy in this scenario not only boosts energy production but also significantly contributes to employment, reflecting the higher labor requirements for installing and maintaining wind power infrastructure. This scenario illustrates the potential socio-economic advantages of integrating RES into the energy portfolio of remote regions.

Scenario 3 demonstrates the highest job creation potential among the three scenarios, with 173 jobs during the construction phase and 13 jobs during the operations phase. The inclusion of solar panels, albeit contributing a small portion of the total energy production, further enhances employment opportunities. This scenario highlights the comprehensive advantages of a diversified hybrid energy system, which not only optimizes energy production and environmental performance but also maximizes socio-economic benefits through increased job creation.

5.5 Sustainability Analysis

A comprehensive sustainability analysis requires evaluating energy production scenarios based on three key criteria: economic viability, environmental impact, and social benefits. This analysis will compare the three scenarios under consideration, examining their performance across these dimensions to determine the most sustainable energy production strategy for Arviat.

Evaluating the three scenarios across economic, environmental, and social criteria reveals distinct advantages and limitations for each; As depicted in Figure 12, Scenario 1 is the least favorable due to its high costs, significant environmental impact, and minimal job creation. Scenario 2 exhibits strong economic and environmental performance with substantial job creation, making it highly sustainable. It has the lowest LCOE and achieves the highest emission reductions.

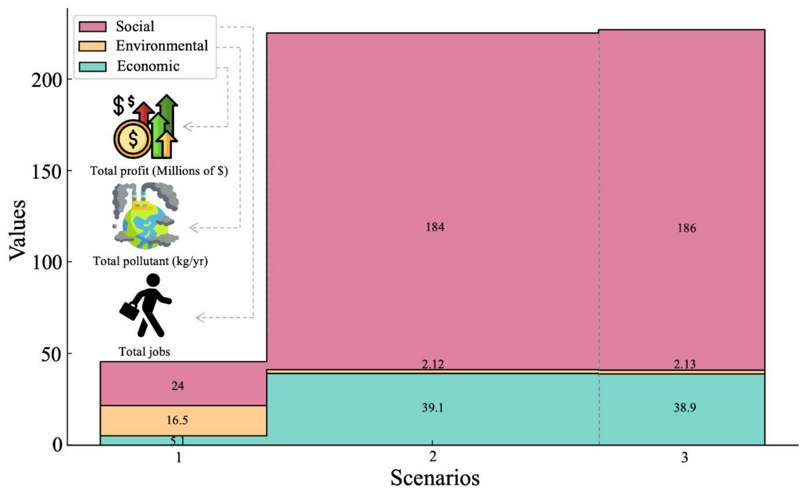

Figure 12. Sustainability analysis

Scenario 3 presents slightly higher costs but maintains competitive margins, significant environmental benefits, and the highest job creation, offering a balanced and comprehensive sustainability profile.

Overall, Scenario 2 emerges as the most sustainable option, offering the best balance of economic and environmental performance, along with significant social benefits. Integrating wind energy with diesel generators and storage provides a viable path for RCs like Arviat to achieve sustainable and profitable energy production while substantially reducing emissions and creating jobs.

One limitation of this study is the reliance on simulated data for wind and solar resources. Future research could benefit from field data collection to validate these findings.

Policymakers should consider incentivizing the adoption of hybrid energy systems through subsidies or grants, particularly in regions where diesel dependency is high. Energy planners are encouraged to explore the integration of storage solutions to enhance the reliability of renewable energy systems.

6 Conclusions

The analysis clearly demonstrates that incorporating sustainable sources of energy like wind and solar into the energy production mix, along with traditional diesel generators, significantly enhances economic performance. These hybrid systems not only reduce production costs but also maximize profit margins, making them more viable and sustainable options for large-scale electricity production.

This paper assesses the feasibility and sustainability of a microgrid energy system in Arviat, Nunavut, comparing three scenarios: a diesel-only system, a diesel-wind hybrid system, and a diesel-wind-solar hybrid system. Using HOMER software for simulation, Scenario 2, which integrates wind turbines with diesel generators, proves to be the most sustainable. It offers the lowest levelized cost of electricity, substantial emission reductions, and significant job creation, making it the best option for Arviat.

In contrast, Scenario 1 is the least favorable due to high costs and minimal job creation. Scenario 3, while more costly than Scenario 2, still provides competitive economic margins and the highest job creation. These findings highlight the significance of incorporating clean energy sources, particularly wind energy, to achieve a sustainable and economically viable energy solution for remote areas.

Looking forward, there are several areas for future research that could build on the findings of this study. First, further investigation into the long-term impacts of hybrid energy systems on the economic development of RCs is warranted. Understanding how these systems can contribute to long-term economic resilience and energy independence is crucial for policy development. Second, research could explore the integration of emerging renewable technologies, such as advanced energy storage systems or tidal energy, into hybrid configurations. These technologies could potentially enhance system reliability and further reduce environmental impacts.

Additionally, the social implications of transitioning to hybrid energy systems in remote Arctic communities warrant closer examination. Future studies should consider how these energy transitions impact community dynamics, including changes in employment patterns, social cohesion, and cultural practices related to energy use. Finally, a broader assessment of the environmental impacts, including the potential effects on local wildlife and ecosystems, would provide a more comprehensive understanding of the sustainability of hybrid energy systems.

In conclusion, this study highlights the significant potential of hybrid energy systems, particularly those integrating wind energy, to transform the energy landscape of remote Arctic communities like Arviat. The adoption of such systems not only aligns with global sustainability goals but also offers practical benefits in terms of economic viability, environmental stewardship, and social development. As the world moves towards cleaner energy solutions, the findings of this study provide valuable insights for policymakers, energy planners, and community stakeholders seeking to implement sustainable energy systems in remote and challenging environments.

Data Available

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 that they have no conflicts of interest.

References

[1] C. A. John, L. S. Tan, J. Tan, P. L. Kiew, A. M. Shariff, and H. N. Abdul Halim, "Selection of renewable energy in rural area via life cycle assessment-analytical hierarchy process (LCA-AHP): A case study of Tatau, Sarawak," *Sustain.*, vol. 13, no. 21, p. 11880, 2021. https://doi.org/10.3390/su132111880

[2] M. Arriaga, C. A. Cañizares, and M. Kazerani, "Long-term renewable energy planning model for remote communities," *IEEE Trans. Sustain. Energy*, vol. 7, no. 1, pp. 221–231, 2016. https://doi.org/10.1109/TSTE.2015.2483489

[3] "Remote communities energy database," Apr., 2024. https://open.canada.ca/data/en/dataset/0e76433c-7aeb-46dc-a019-11db10ee28dd

[4] E. Dowdell and S. Patel, "Nunavut energy market profile." University of Alberta Future Energy Systems, 2024. https://www.futureenergysystems.ca/public/download/documents/70235

[5] H. Pinto and I. D. Gates, "Why is it so difficult to replace diesel in nunavut, Canada?" *Renew. Sustain. Energy Rev.*, vol. 157, p. 112030, 2022. https://doi.org/10.1016/j.rser.2021.112030

[6] M. de Witt, H. Stefánsson, Á. Valfells, and J. N. Larsen, "Energy resources and electricity generation in arctic areas," *Renew. Energy*, vol. 169, pp. 144–156, 2021. https://doi.org/10.1016/j.renene.2021.01.025

[7] S. Bahramara, M. P. Moghaddam, and M. R. Haghifam, "Optimal planning of hybrid renewable energy systems using homer: A review," *Renew. Sustain. Energy Rev.*, vol. 62, pp. 609–620, 2016. https://doi.org/10.1016/j.rser.2016.05.039

[8] J. Knowles, *Power Shift: Electricity for Canada's Remote Communities*. The Conference Board of Canada, Ottawa, 2016.

[9] I. Das and C. A. Canizares, “Renewable energy integration in diesel-based microgrids at the Canadian Arctic,” *Proceedings of the IEEE*, vol. 107, no. 9, pp. 1838–1856, 2019. https://doi.org/10.1109/JPROC.2019.2932743

[10] M. de Witt, H. Stefansson, and A. Valfells, “Energy security in the Arctic: Policies and technologies for integration of renewable energy,” in *Arctic Yearbook*. Arctic Portal, 2019, pp. 189–196.

[11] M. Jeffries, J. Richter-Menge, and J. E. Overland, “Arctic report card 2015,” National Oceanic and Atmospheric Administration, 2023. http://www.arctic.noaa.gov/Report-Card

[12] M. Arriaga, C. A. Cañizares, and M. Kazerani, “Northern lights: Access to electricity in Canada’s northern and remote communities,” *IEEE Power Energy Mag.*, vol. 12, no. 4, pp. 50–59, 2014. https://doi.org/10.1109/MPE.2014.2317963

[13] M. de Witt, H. Stefánsson, . Valfells, and J. N. Larsen, “Availability and feasibility of renewable resources for electricity generation in the arctic: The cases of Longyearbyen, Maniitsoq, and Kotzebue,” *Sustain.*, vol. 13, no. 16, p. 8708, 2021. https://doi.org/10.3390/su13168708

[14] A. Garcia-Bernabeu, F. Mayor-Vitoria, M. Bravo, and D. Pla-Santamaria, “Financial risk management in renewable energy projects: A multicriteria approach,” *J. Manag. Inf. Decis. Sci.*, vol. 22, no. 4, pp. 360–371, 2019. http://hdl.handle.net/10251/164156

[15] A. L. Vernay, M. Sohns, J. Schleich, and M. Haggège, “Commercializing sustainable technologies by developing attractive value propositions: The case of photovoltaic panels,” *Organ. Environ.*, vol. 33, no. 2, pp. 220–244, 2020. https://doi.org/10.1177/1086026619853797

[16] 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

[17] N. C. McDonald and J. M. Pearce, “Community voices: Perspectives on renewable energy in nunavut,” *Arctic*, vol. 66, no. 1, pp. 94–104, 2013. https://doi.org/10.14430/arctic4269

[18] S. Rahmouni, B. Negrou, N. Settou, J. Dominguez, and A. Gouareh, “Prospects of hydrogen production potential from renewable resources in Algeria,” *Energy Fuel Technol.*, vol. 42, no. 2, p. 1383–1395, 2016. https://doi.org/10.1016/j.ijhydene.2016.07.214

[19] A. Boute, “Off-grid renewable energy in remote arctic areas: An analysis of the Russian far east,” *Renew. Sustain. Energy Rev.*, vol. 59, pp. 1029–1037, 2016. https://doi.org/10.1016/j.rser.2016.01.034

[20] R. Allen, D. Brutkoski, D. Farnsworth, and P. Larsen, “Sustainable energy solutions for rural Alaska.” Energy Markets and Policy Department, Energy Analysis and Environmental Impacts Division, 2016. https://emp.lbl.gov/sites/all/files/lbnl-1005097.pdf

[21] “Potential for wind energy in nunavut communities,” 2021. https://www.qec.nu.ca/sites/default/files/potential_for_wind_energy_in_nunavut_communities_2016_report_0.pdf

[22] G. Poelzer, G. H. Gjorv, G. Holdmannand, N. Johnson, B. M. Magnússon, L. Sokka, M. Tysyachnyouk, and S. Yu, “Developing renewable energy in arctic and sub-arctic regions and communities: Working recommendations of the fulbright arctic initiative energy group.” International Centre for Northern Governance and Development, University of Saskatchewan, Saskatoon, Canada, 2016. https://canadacommons-ca.qe2a-proxy.mun.ca/artifacts/1192981/developing-renewable-energy-in-arctic-and-sub-arctic-regions-and-communities/1746101/

[23] “The global energy landscape is going through major shifts: What does this mean for value pools in energy?” 2024. https://www.mckinsey.com/industries/oil-and-gas/our-insights/oil-and-gas-blog/the-global-energy-landscape-is-going-through-major-shifts-what-does-this-mean-for-energy-value-pools

[24] “The challenges of integrating variable renewable energy,” 2024. https://www.bcg.com/publications/2021/addressing-variable-renewable-energy-challenges

[25] “NREL study identifies the opportunities and challenges of achieving the U.S. transformational goal of 100% clean electricity by 2035,” 2022. https://www.energy.gov/eere/articles/nrel-study-identifies-opportunities-and-challenges-achieving-us-transformational-goal

[26] F. Farahmand, J. King, D. Ghahremanlou, P. Sakthi, M. Reza, and M. Jafari, “A comprehensive systematic overview of Canadian hydrogen supply chains downstream,” *J. Sustain. Dev.*, vol. 17, no. 2, p. 1, 2024. https://doi.org/10.5539/jsd.v17n2p1

[27] 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, p. 1, 2023. https://doi.org/10.5539/JSD.V17N1P1

[28] R. A. Al Hasibi and A. Haris, “An analysis of the implementation of a hybrid renewable-energy system in a building by considering the reduction in electricity price subsidies and the reliability of the grid,” *Clean Energy*, vol. 7, no. 5, pp. 1125–1135, 2023. https://doi.org/10.1093/CE/ZKAD053

[29] S. Ahmed, A. Ali, and A. D’Angola, “A review of renewable energy communities: Concepts, scope, progress,

challenges, and recommendations," *Sustain.*, vol. 16, no. 5, p. 1749, 2024. https://doi.org/10.3390/SU16051749

[30] 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*, 2022, pp. 589–595. https://doi.org/10.1109/IEMCON56893.2022.9946552

[31] A. Osmani and J. Zhang, "Optimal grid design and logistic planning for wind and biomass-based renewable electricity supply chains under uncertainties," *Energy*, vol. 70, pp. 514–528, Jun. 2014. https://doi.org/10.1016/J.ENERGY.2014.04.043

[32] 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

[33] A. Maliat, S. Kotian, S. Shirinnezhad, and D. Ghahremanlou, "Enhancing sustainability in Hopedale,Newfoundland and labrador, through hybrid microgrid system design," *Power Eng. Eng. Thermophys.*, vol. 3, no. 1, pp. 58–76, 2024. https://doi.org/10.56578/peet030105

[34] B. Liu and J. M. Vanderleeuw, "Economic development priorities and central-city and suburb differences," *Am. Polit. Res.*, vol. 32, no. 6, pp. 698–721, 2004. https://doi.org/10.1177/1532673X03262392

[35] M. Taylor and P. Ralon, "Renewable power generation costs in 2019," *International Renewable Energy Agency (IRENA)*, 2020.

[36] J. T. Carlson, "Integrating social concerns into regional renewable energy resource assessments: A case study in Rigolet, NL, Canada," *ProQuest Dissertations & Theses*, 2022. https://mun.primo.exlibrisgroup.com/permalink/01MUN_INST/1nn7388/cdi_proquest_journals_2786887402

[37] E. M. Amewornu and N. I. Nwulu, "A framework for the techno-economic and reliability analysis of grid-connected microgrids," *J. Eng. Des. Technol.*, vol. 19, no. 3, pp. 659–685, 2021. https://doi.org/10.1108/JEDT-05-2020-0185

[38] A. Kumar, A. R. Singh, R. S. Kumar, Y. Deng, X. He, R. C. Bansal, P. Kumar, and R. M. Naidoo, "An effective energy management system for intensified grid-connected microgrids," *Energy Strategy Rev.*, vol. 50, p. 101222, 2023. https://doi.org/10.1016/j.esr.2023.101222

[39] S. Mahmudi, "The financial metrics and risk management tools in supporting renewable energy investment," *Int. J. Acad. Res. Bus. Soc. Sci.*, vol. 12, no. 8, pp. 238–249, 2022. https://doi.org/10.6007/IJARBSS/v12-i8/14516