Article

Availability and Feasibility of Renewable Resources for Electricity Generation in the Arctic: The Cases of Longyearbyen, Maniitsoq, and Kotzebue

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Abstract: Currently, the dominant energy source for electricity generation in the Arctic is diesel, which is well proven for Arctic conditions. However, diesel is expensive in the Arctic, often due to long and complicated fuel transportation routes, and so inhabitants of Arctic communities can face high electricity costs. This paper investigates whether renewable energy resources can be harvested in a feasible and cost-competitive manner. The paper highlights which renewable energy resources are generally available in the Arctic and analyzes how renewable resources, such as hydropower, wind, and photovoltaics, can be used. Furthermore, we present three specific case studies to provide in-depth insight. A simulation with different energy generation scenarios using different renewable energy sources and penetration levels was performed for each case. The results indicate that renewables can be a cost-competitive option and that the optimal mix of renewables varies for different communities. Stakeholders and experts from the case study communities were also interviewed and their responses indicated a general acceptance of renewables.

Keywords: Arctic; renewable energy; energy transition; electricity generation; energy economy; climate change

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1. Introduction

Remote Arctic communities often face high electricity prices, which place a considerable cost burden on the population of the North. Therefore, it is important to find new ways of providing electricity to remote communities facing high electricity prices. This research examines whether renewable energy resources can be used to provide affordable electricity to remote Arctic communities. It is critical for a successful transition process toward renewables that the renewable resources can be harvested in a manner that is both technically feasible and economically viable. This study examines the case for renewables in three Arctic communities: Longyearbyen on Svalbard, Maniitsoq in Greenland, and Kotzebue in Alaska. The availability of renewable energy resources is highlighted, including how they can be harvested in an economically feasible manner. For each community, a simulation-based scenario analysis with different energy options and different shares of renewables is presented, with a comparison of their feasibility. The scenario analyses were based on results from a literature review and data collected during field visits to all three case study communities.

2. Background

The three case study communities face an Arctic climate with harsh, cold conditions [1–3]. In the Arctic, the warmest monthly average temperature is below 10 °C, and during winter, the temperature can drop to −60 °C [4]. The harsh weather conditions can

affect technologies' material properties and reliability. In addition to the harsh climate, Arctic communities are often remote, with distances between communities ranging from tens to hundreds of kilometers. These communities have limited road connections with neighboring communities and have adapted to the environment using different transportation methods. Some transportation methods can be used seasonally, such as all-terrain vehicles, snowmobiles, dogsleds, or boats. Air transport is non-seasonal, though it is dependent on daily weather conditions. Owing to a lack of road infrastructure, communities have limited access to electricity grids. Overland lines are often built next to roads or railways to facilitate construction and maintenance [5]. In terms of electricity supply, such communities must use independent, self-sufficient electricity grids called 'islanded grids' [6,7].

Diesel is the dominant energy source used to generate electricity in remote Arctic communities and is used by approximately 80% of remote Arctic communities in the USA, Canada, Greenland, and Norway [8,9]. A common problem in the Arctic is the reliance on outdated diesel generators, which must be replaced often [10]. A study of the remaining 20% of remote Arctic communities revealed that they use several renewable energy sources, predominantly hydropower, as illustrated by Figure 1. The bulk of the installed hydropower capacity is concentrated in a few larger communities with high electricity demands [9]. Wind and solar energy generation sites can be found in the remote Arctic, but these currently account for a small proportion of the electricity mix.

Figure 1. The figure shows the share of electricity generation (in MWh) among diesel generators, wind generators, and generation using hybrid systems. Hybrid systems combine diesel generators with non-dispatchable energy resources, such as wind and photovoltaic (PV) power.

In recent decades, diesel has proven to be a reliable and suitable energy source for Arctic communities. Diesel can be stored with minimal losses, has high energy density, and can be used in cold conditions, where the diesel generator's cold start is possible within a short time frame [11]. Nevertheless, diesel use has several disadvantages. First, it is associated with the emission of greenhouse gases and particulate matter [12,13]. Second, diesel transportation to communities is a difficulty specifically associated with diesel use in the Arctic. Three different means of transportation are used: along ice roads during winter, on barges during summer, and by air all year round [14]. Transportation along ice roads becomes increasingly complicated as the ice road season becomes shorter and the ice thins

owing to the impact of climate change [8]. The opening time of an ice road depends on latitude. Furthermore, annual variations are observed depending on weather conditions. These variations diminish the ice roads' utility and increase the risk of accidents that may lead to fuel spills, which can be traced in the food chain [15].

Conversely, the operational period for barge transport has been extended owing to the effects of climate change. However, the community must be located along a navigable river or at the shoreline. Air transport will only be employed in emergencies or if the above-mentioned options are not feasible, since air transport is costly [13,16,17]. All options require considerable planning and favorable weather conditions. Since diesel is delivered only annually in most cases, extensive diesel storage facilities are required to store the required fuel for over a year [18]. This is essential to ensuring energy security in remote communities—problematic fuel delivery and storage results in high fuel prices [8,19], which in turn leads to high electricity prices. High fuel prices and environmental impacts are driving forces for energy transition toward locally available and sustainable energy resources in remote Arctic communities.

2.1. Energy Sources

All the most common renewable energy sources are available in the Arctic. In remote areas with harsh weather conditions, mature and reliable technology that has been robustly proven under the given climate conditions and requires minimal maintenance is vital. Reliable energy technology is also critical for remote communities that rely on islanded electricity supply systems. Reliability is often dependent on regular maintenance and skilled operators, but it can be challenging for electricity providers in remote communities to find and maintain skilled workforces [1,17]. For maintenance personnel coming from external companies, dispatching personnel to remote communities at short notice may be challenging. The same may be said of spare parts owing to unpredictable, harsh, and variable weather patterns with limited travel options [20]. In the sections that follow, mature technologies for Arctic areas, such as geothermal power, wind power, solar power, and hydropower, will be briefly introduced. De Witt et al. [21] elaborated further on energy resources and electricity generation technologies in the Arctic.

Geothermal power is a mature and well-proven technology under harsh Arctic conditions, and is used extensively to generate heat and electricity in several locations, such as Iceland [22]. Geothermal power requires the availability of sufficient geothermal energy sources, which are rare in Arctic regions. High geothermal potential mainly occurs at tectonic plate boundaries or hot spots, such as at the ring of fire on the Pacific coast of Alaska and Russia. Another hot spot is located under Iceland, while a lower temperature area is found in eastern Canada and western Greenland [22].

For wind power, regular wind speed is essential. Excessively high wind speeds will necessitate that the turbine be shut down for safety reasons [23], whereas if wind speeds are too low, the turbine will operate below its rated capacity. In Greenland, for example, high winds are not uncommon [4]. Generally, coastal areas with a constant breeze above 5 m/s are most suitable for wind turbines [16].

Solar radiation in Arctic areas shows significant seasonal changes, with up to 24 h of daylight during the summer and the possibility of no sunlight at all during winter. Nevertheless, solar energy is quite attractive in the Arctic. In the spring, when sunlight and snowy ground coincide, solar radiation is reflected by the snow, increasing the photovoltaic (PV) panels' yield [24]. Another factor favoring the use of PV panels in Arctic regions is that they are more efficient in cold than in warm climates [24].

The requirements for hydropower vary depending on the proposed plant's size. A smaller run-of-the-river plant can operate without a reservoir, although it may then be susceptible to drought. For large-scale hydropower plants, elevated reservoirs can balance the flow to meet daily seasonal variations in demand and river flow.

In this work, we will focus on the use of the following three commonly available renewable energy sources for the generation of electricity in the Arctic:

1. Hydropower, which was first introduced to the Arctic more than 100 years ago [25].
2. Wind power, which has been in use for several decades [26].
3. Photovoltaic electricity, which is relatively new in the Arctic [27].

Geothermal power is excluded owing to its limited availability.

2.2. Energy Storage

Energy storage is crucial for the successful transition to renewables in islanded energy systems (see Section 2.3). The need for storage is understood in terms of different time scales. Energy storage on the shortest time scale is required to ensure grid stability in terms of voltage and frequency. Therefore, a spinning reserve from a generator or flywheel is often used. An intermediate time scale for meeting daily or weekly variations in supply and demand is often managed using battery storage, covering both short-term and intermediate-term energy storage. Long-term storage is needed to meet seasonal variations. Some renewable sources, such as solar energy and run-of-the-river hydropower, are only available seasonally. An example of long-term energy storage technology is pumped hydro storage (to the author's knowledge, this technology has not yet been proven under Arctic conditions, but it is technically similar to a conventional hydropower plant), whereby water is pumped into a high-elevation reservoir where excess energy is available. In cases of energy shortage, water flows down, as it does in a conventional hydropower plant. Long-term energy storage is essential for reaching high proportions of renewables if significant seasonal variations affect the resource. Several exciting development projects are imminent for long-term energy storage solutions, including hydrogen, various gravitational storage solutions, and underground thermal storage. Hydrogen has the potential for long-term energy storage and fuel for other purposes. A review of the literature indicates that significant research and development in the energy storage area is ongoing. Various types of gravitational storage, aside from pumped hydropower, have been considered. The Swiss start-up Energy Vault offers a small-scale energy storage solution for flat regions [28]. A crane with an electrical motor/generator elevates the weight to convert electricity into potential energy. If energy is required, the weights can be lowered to generate electricity. Hunt [18] discusses mountain gravity energy storage with a concept similar to that used by Energy Vault: rather than cranes, however, Hunt suggested using height differences in mountainous regions to store energy [18].

Another option is to convert electricity into heat. Excess electrical energy can heat a thermal reservoir, which can then release heat when required after an extended period. Thermal underground storage has been tested under sub-Arctic conditions but not in Arctic areas with permafrost [29]. For short-term or immediate solutions, water can be electrically heated and fed into the district heating system [26]. If no such system is available, electricity can be used directly to heat individual houses. For this purpose, smart night storage heaters are used [30].

2.3. Energy Systems

Energy systems in remote Arctic communities are based on islanded energy grids. To introduce renewable energy resources, the grid structure must be adjusted to the new situation and the grid must be taken one step further to form an island microgrid. A microgrid is defined as a network of distributed generators, such as renewables (see Section 2.1), energy storage (see Section 2.2), and loads that cooperate as a single controlled generator or load [31]. In small energy systems with non-dispatchable renewable energy sources, such as wind and solar PV, the penetration level from non-dispatchable energy sources is critical. The penetration levels are classified as low, medium, and high, and can be calculated using Equation (1). Low penetration means that up to 20% of the annual average is derived from non-dispatchable resources. The diesel engine must still run full-time, but the diesel load is reduced, and all non-dispatchable energy goes to the primary energy load. The diesel engine can stabilize voltage and frequency; no supervisory control system is required for that purpose [32]. Medium penetration ranges between 20% and 50%

of the annual average. Secondary loads are added to the system to take peak loads [32]. The diesel engine still runs full-time, and the control system is relatively simplistic [32]. High penetration accounts for a penetration level above 50% of the annual average. The diesel generator can be shut down during periods of high energy generation. A sophisticated control system is needed along with components to regulate voltage and frequency [32].

$$\text{Average penetration [\%]} = \frac{\text{non-dispatchable energy production [kWh]}}{\text{primary energy demand [kWh]}} \quad (1)$$

A more comprehensive overview of the availability of renewable energy resources in the Arctic can be found in [9]. This paper adds more specific information to the existing literature [21] by presenting three case studies to analyze the current status of energy systems and the specific potential and feasibility of transitioning to locally available renewable energy resources. The paper further examines how local societies perceive renewables and renewable energy use and how resources are anchored in society, policies, and the economy. Section 3 presents the research methodology used to collect information, select case studies, and to study the potential use of alternative energy sources for each case study. Section 4 presents the main results from the case studies, which are assessed in terms of economic, environmental, and technical factors. Section 4 provides a brief general discussion of the potential for renewable energy resource use in the Arctic, followed by conclusions in Section 5.

3. Research Methodology

3.1. Research Objectives

This study's main objective is to investigate which renewable energy options are feasible in remote Arctic communities. The guiding research question asks whether renewable energy resources may be a feasible option that can help remote Arctic communities overcome diesel's high energy costs and environmental impact. The following sub-questions are considered:

- Which renewable sources are locally available?
- Is harvesting available energy sources economically feasible?
- Are local inhabitants likely to accept energy harvesting technology?

Answering these questions can contribute to solving some of the issues and challenges facing Arctic communities as introduced in the literature review. The issues that Arctic communities experience in relation to energy can be attributed to the affordability of energy, energy security, and the environmental impact of energy extraction, transportation, and generation. It is assumed that renewables can help increase the affordability of electricity and support an increase in energy security for Arctic inhabitants. The research attempts to push the boundaries for the share of renewables even further by shedding light on possible energy transition pathways and how they might affect electricity generation costs. The present study focuses on feasibility, whereas the structure of the transition process lies beyond the scope of this paper.

3.2. Case Studies

This study aims to investigate how the integration of renewables might work under real-world conditions in Arctic communities. To create real-world conditions, three case studies were selected: the communities of Longyearbyen, Maniitsoq, and Kotzebue. The case study approach allowed us to highlight regional variations between various renewable energy sources and grid structures. Figure 2 presents a map showing the communities' locations. All three communities were visited for onsite fieldwork, with visits lasting from one to two weeks. The primary goal was to obtain a first-hand impression of the communities and to assess how energy is generated and used locally. Interviews were conducted to refine our understanding of energy generation and use (see Section 3.3.2) in the communities. Additionally, data were gathered through visits to electricity generation

facilities. Energy-related facilities, such as district heating plants, were also visited, as these play an essential role in the overall energy framework. The other side of the energy system is energy consumption: several key energy consumers, such as hospitals and various commercial and industrial buildings, were visited to obtain detailed insights. A brief overview of the key information pertaining to the communities is provided below. Further details on the similarities and differences will follow in Section 4.1. The three communities share the following similarities:

- They are located on the shoreline and are not connected to a permanent road network or electricity grid in the remote Arctic.
- Population size ranges from 2000 to 3000 inhabitants.
- Transportation infrastructure is limited; communities are primarily connected via planes or boats, which means that port and airport infrastructure is available.

Figure 2. The locations of the communities for the case study: Longyearbyen, Maniitsoq, and Kotzebue. Source: Google Earth US Dept of State Geographer Image Landsat/Copernicus NOAA, US Navy, NGA, GEBCO.

Significant differences also exist between the communities, including:

- Differences in the energy mix.
- Differences in geography and physical environment; the availability of energy resources differs depending on the geographical situation.
- Environmental policy based on the country's targets.
- The proportion of the population who are indigenous.

Differences in energy mix were an essential factor in the selection of communities. It was important to the study to include communities at different stages of the energy transition pathway to test the robustness of the case study simulation and how well it represents the real world.

3.3. Literature Review and Data Collection

3.3.1. Structure of the Literature Review

The literature review focuses on renewable energy resources and electricity generation in the Arctic. The literature review began as a scoping study, which helped create an

initial overview of the extent of previous research in the respective areas [33]. The scoping literature review also provides a starting point for a more detailed literature review [34].

For this research, a backward approach appeared to be more efficient. We followed up on the citations for relevant information or passages and added the cited sources to the reading list. We deemed the backward approach to be more precise. For a small number of particularly relevant papers, we used a forward-oriented approach.

3.3.2. Interviews and Databank Harvesting

Primary data were gathered through databank harvesting and interviews, adding greater detail to the study. The aim of the interviews was to identify possible problems and needs associated with renewable energy and energy in general in the respective communities. Such information was necessary to analyze possible transitions. We also obtained some insights into the general acceptance of renewables. The interviews were conducted as semi-structured, one-on-one interviews. Semi-structured interviews have the advantage of having a guiding structure and leading questions [35,36]. The guiding structure leaves space to collect information on topics that may not have occurred to the interviewer during the preparation [37,38]. The interviewer can steer the interview and go into further detail if the interviewee raises a relevant topic of particular importance for complex issues [39]. The person-to-person interaction can help prevent any misunderstandings that might arise during the interview. Each interview concluded with a reflection on the main findings to ensure the correctness of the information [39]. The one-on-one interviews were conducted in the field, and thus it was necessary to visit the three communities. We visited the three selected communities in the period between winter 2018 and summer 2019 to conduct around 40 in-depth interviews with professionals with different areas of expertise, which allowed us to obtain first-hand impressions of the different communities. The above-mentioned visits to energy-related facilities and industries facilitated the interviews. Since most facilities had several staff members, it was possible to interview local managers and/or chief engineers/operators. On the industry side, we interviewed business owners or managers. We also interviewed local government representatives for energy, the environment, infrastructure, and buildings. The last group of interviewees consisted of residential consumers. The different groups were selected based on the assumption that they held different views on energy. A general hypothesis of the study was that environmental advocates tend to support the harvest of renewables and that the cost of energy is secondary and, by contrast, that business owners and consumers primarily care about energy prices while sustainability comes second. The interviews collected information regarding the interviewees' different backgrounds and perspectives on:

- The current state of energy conversion.
- Experience of the energy transition.
- Recognition of energy policy.
- Expectations for future energy policy.
- Different energy sources and their environmental impacts.
- Renewable energy sources and their effect on the traditional lifestyle.
- Energy security.
- The current state of technology and technical options for the future.

Another source of information used in this research was primary data collected through database harvesting. The databases used were the 'Alaska Energy Gateway' and the database of Nukissiorfiit, the Greenlandic national utility company. Some databases are publicly accessible, while others offer limited accessibility owing to considerations of confidentiality.

3.4. Scenario Analysis and Simulation

The models for the scenarios are, like every model, simplified representations of real-world problems that lead—to some degree—to idealized systems. The research design sought to anticipate the idealization by validating the simulation. Therefore, one scenario

with a significant amount of renewables with real-world data was integrated into the scenario analyses. Different scenarios were constructed to analyze energy generation using different renewable energy sources at various penetration levels. The scenarios were designed independently using the information collected from the interviews and literature review. The underlying framework for all scenarios was the same for all three cases. The interviews generated further data on renewables, rendering the analysis more comprehensive and precise. Moreover, the visit offered a more in-depth view of the current situation, fuel price, fuel consumption, and capacity factor. The capacity factor is the ratio of maximal possible electricity generation to actual electricity generation. The scenario design was developed according to the three penetration levels (see Section 2.3). Scenarios with different resources at different penetration levels were created for each community. The scenarios aim to forecast the feasibility of various energy options. Forecasting scenarios can be challenging, since it is not always possible to predict how different actors will behave in the future [40]. With an increasing time horizon, this uncertainty can increase. The time horizon for the scenario analyses was selected in accordance with the technical lifetime of most technologies, which is considered to be 30 years. Over the time horizon, the net present value of the electricity generation cost was calculated. Two main variables were needed for the calculation: technology selected (see Sections 2.1 and 2.2) and renewable energy penetration level (see Section 2.3). The set of secondary variables required is explained in greater detail below and is presented in Table 1.

Table 1. Overview of the assumptions for the scenario analysis.

Name	Value	Unit	Source
Diesel Price *		\$ per liter	
Capacity Factor *		%	
Fuel Consumption *		l/kWh	
CO ₂ Emission Diesel	2.68	kg/L (diesel)	Calculated
CO ₂ Price	30.00	\$/t	[41]
O and M Diesel	0.02	\$/kWh	[42]
O and M Solar	9	\$/kW	[43]
O and M Wind	3	%	[44]
O and M Hydro	2	%	[45]
Install. Cost Solar	2500	\$/kW	[27]
Install. Cost Wind	2500	\$/kW	[46]
Install. Cost Hydro	7000	\$/kW	[22]
Capacity Factor PV	15	%	[27]
Capacity Factor Wind	33	%	[47]
Capacity Factor Hydro	50	%	[48]

Note: * variable depending on the community.

The scenario analysis examines the introduction of renewable energy resources, such as PV, wind, and hydropower, at different penetration levels as represented. The research investigates the cost aspects of integration over a 30-year period. On the renewable cost side are installation, operation, and maintenance costs. These costs of integrating renewables are compared to a base case. The base case assumes that an existing fossil-fueled power plant generates electricity. Since the age of the existing power plant is unknown, the urgency with which the diesel generator should be replaced is also unclear. This assumption favors diesel as an energy source. Using the real age of the diesel generator would have made it impossible to compare the three different cases. The base case involves operation and maintenance costs.

Table 1 provides an overview of the assumptions made for the input of the scenario analysis. Costs that differ from case to case, such as fuel price, capacity, and fuel consumption, are left blank in Table 1 and are shown in the graphs of the corresponding instances. The aforementioned blank values were collected during the field visits and represent real-life situations in the communities. The values that were the same for all cases mainly resulted from the literature review and data gathered from interviews.

The scenario analysis assumes a CO₂ cost of \$30 per ton following the European CO₂ certificate prices [41]. The European CO₂ certificate trading system was selected as a reference value since it has been proven effective for reducing CO₂ at a low price. Climate change simulation programs, such as En-ROADS (<https://www.climateinteractive.org/tools/en-roads/>, accessed on 25 July 2019), can lead to significantly higher CO₂ price recommendations. Setting the price of CO₂ to the lower end is more favorable for the conventional energy generation method. Moreover, the low CO₂ price adds more security to the results. Nevertheless, the impact of CO₂ costs was also investigated. On the lower end of the payback time, the effect is minor. The change in payback time differs by one year for a CO₂ price change from \$0 to \$100 per ton of CO₂. Higher CO₂ prices increase the payback time by approximately four years.

If a battery is used, it is expected that a replacement will be required after a lifetime of 15 years [49]. The purchase of a new battery stack was calculated according to current prices. It may be assumed that prices will drop in response to technological improvements. The scenario analysis was conducted with a conservative assumption of battery prices whereby they remain constant over time. The capacity factor of PV has a significant impact on economic feasibility. Changes in the capacity factor are likely attributable to different latitudes. A lower capacity factor can negatively impact feasibility.

Table 2 shows the different penetration levels with renewables used for the scenario analysis. In the case of high wind penetration, 60% was selected to maintain the battery storage amount at a reasonable level. No high-penetration PV scenario is presented because no mature long-term energy storage was available to shift the energy from summer to wintertime. Batteries are not suitable for seasonal energy shifts. A pumped hydropower plant may offer another option, but hydropower would be more cost efficient than PV as a primary energy source. Other, less mature, long-term energy storage options have been explained in detail above. In the case of Kotzebue, values were taken from the wind farm.

Table 2. Overview of the penetration levels used in the case studies in Section 3.1.

Name	Energy Generation	Penetration Level
Base Case	Diesel	0%
Scenario I: Low PV	Photovoltaics	10%
Scenario II: Mid PV	Photovoltaics	30%
Scenario IV: Low Wind	Wind	10%
Scenario V: Mid Wind	Wind	30% *
Scenario VI: High Wind	Wind	60%
Scenario VII: Low Hydro	Hydro	10%
Scenario VIII: Mid Hydro	Hydro	30%
Scenario IX: High Hydro	Hydro	90%

Note: * in Kotzebue, the value of 25% was taken to represent the actual situation.

4. Results and Discussion

4.1. Case Study

The overview presented in Table 3 indicates that all communities already include at least small proportions of renewable energy in their energy mixes. In the Maniitsoq and Longyearbyen cases, the proportion appears negligible—less than one percent. However, this at least shows some willingness to include renewables in the energy mix, as will be explained in greater detail below.

Table 3. Overview of the three case study communities: population, energy demand, installed capacity, and penetration of renewables.

Name	Longyearbyen	Maniitsoq	Kotzebue
Population	2144	2534	3153
Energy Demand	43,035 MWh	12,051 MWh	21,925 MWh
Installed Capacity	12.3 MW	9.6 MW	15 MW
RE Penetration	0.06%	0.1%	18%

4.1.1. Longyearbyen

Longyearbyen is located on the island of Svalbard (78° 13' N, 15° 38' E). It has a population of around 2100 inhabitants. Longyearbyen is a non-indigenous community; the population is multi-national, and many scientists and tourism sector workers live there. In earlier times, coal mining was a significant economic sector in Longyearbyen. Today, the community has only one active mine, primarily for local use [50]. Longyearbyen's population has a high turnover, with many people living there for periods of only a few to several months or a couple of years [51].

Energy generation in Longyearbyen is based on coal, with a small proportion of diesel. The coal-fired power station is old, but some modernization has already extended its lifetime. With modernization, the power plant may be in operation until 2038, but the local coal reserves are expected to last only until the year 2025 [52]. The coal-fired power plant has an electrical capacity of 7.5 MW, which produces the baseload [53]. Different diesel generators supply a total of 4.8 MW of electricity used for peak loads and as backup generators [53].

The power plant also produces heat for the district heating system. The ratio between heat and electricity produced is 1/3 electricity and 2/3 heat [54]. Next to the power plant, several PV installations can be found—some small, with one large installation at the airport. The airport provider operates the PV plant at the airport. The installed peak capacity is 137 kWp and it was built in two phases in 2017 and 2018 [55]. An experimental small wind turbine also operates at an aviation radio station [55]. Wind data for wind turbines have not yet been measured [54]. The geography appears generally conducive to a hydropower plant. However, geological assessment is advisable since sedimentary rock can be brittle.

The case of Longyearbyen is illustrated in Figure 3. The break-even point of the different renewable energy technologies compared with the base case ranges from 6 to 25 years. The shortest time to reach break-even is in scenario IV low wind, at 6 years. The longest time of 25 years to reach break-even is in scenario II mid PV, owing to the exchange of the battery unit. The low- and medium-penetration cases are close together. The 'high wind' and 'high hydropower' cases show the most significant cost savings. Comparison of both options reveals that hydropower's more significant cost savings come with a high upfront cost. The 'high hydro' case requires an initial investment that is twice as high as the initial investment for the 'high wind' case. The high upfront cost may indicate that the 'high wind' case should be considered the most viable option. For a small community such as Longyearbyen, such an investment may be more feasible. For hydropower, moreover, the geological rock structure's uncertainty must be considered to determine whether a hydropower plant would be feasible or if the construction would cost significantly more than the general estimated construction costs. On the other side of the graph, it is clear that the 'low PV' and 'low wind' cases have a significant impact considering the relatively low investment costs. In terms of the 'low hydro' case, the other low-penetration cases show approximately the same savings over 30 years with significantly lower investment costs. All medium-penetration cases represented have savings that are in accordance with the initial investment costs.

Figure 3. Scenario analysis of possible power generation for Longyearbyen shows the accumulated net present value of cost for power generation with a coal price of 0.1\$/kg; capacity factor of 40%; and fuel consumption of 1.75 kg/kWh. The other input data are explained in Table 1, and the scenarios are presented in Table 2. The current setup is close to the base case; Longyearbyen has 0.06% renewables in the mix.

4.1.2. Maniitsoq

Maniitsoq is a coastal and predominantly indigenous community located on the west coast of Greenland (65°24' N, 52°53' W). Until the end of the 1980s, fishing was the dominant industry, but it suffered a decline due to the migration of fish further north [56]. The community is currently experiencing significant unemployment challenges. A major aluminum smelting project was considered in the recent past until the company withdrew its plans in 2015 [57]. Maniitsoq has a population of around 2500 inhabitants, approximately 5% of whom were born outside Greenland [58].

Maniitsoq has various diesel engines, including a large engine of 1.9 MW and two smaller engines of 1.3 MW. To maximize efficiency in diesel fuel use, a heat recovery system has been installed. This allows engine heat that is usually wasted to be utilized in a district heating system. With this double use, it is possible to increase the yield of used energy from diesel. The old power plant, with an additional three working 900 kW diesel engines, is used as an emergency backup should the three new main engines fail. The old engines have a long cold-start time of approximately 15 min. Maniitsoq has several private PV installations, and the estimated installed PV capacity is between 450 and 500 kWp [27,59].

To provide Maniitsoq with renewable energy, several resources may be mined. PV has already proved suitable and could be extended to more public and private buildings [27].

Another option that could grant Maniitsoq almost full independence from diesel is hydropower. A site suitable for a hydropower plant is located approximately 30 km from the community. The location's potential ranges from 2 MW to 14.5 MW, depending on the expansion stage [59]. Wind power could be another option; currently, no data are available to predict the efficiency of wind turbines in the area. Owing to the community's coastal location, wind power may be assumed to be a feasible option. However, further investigation is required in this regard.

Figure 4 shows that the different renewable energy scenarios have a positive net benefit compared to the current system owing to reduced operation costs over the represented 30-year time horizon. The break-even point can be reached after five years, depending on the various scenarios. The shortest time to reach break-even point—five years—is in scenario IV low wind. Scenario II mid PV does not reach break-even point within the given time frame owing to the exchange of the battery unit. Regarding the wind scenarios, it is interesting that the operation of low and medium penetration has approximately the same cost-saving effect over the simulated time. This is due to the replacement of the battery stack in the medium-penetration scenario. The 'low PV' and 'low wind' cases offer significant cost-saving benefits for little investment, making them suitable options when available funding for large-scale solutions is limited. The 'low hydro' and 'mid wind' cases have high investment costs with cost savings on par with the above-mentioned 'low PV' and 'low wind' cases. The 'high wind' case offers good cost-saving benefits, but the following two options are more financially feasible. The 'mid hydro' and 'high hydro' cases have high investment costs, but their cost savings over time are favorable relative to the investment cost. Both cases present cost data in favor of more significant investments in renewables.

Figure 4. Scenario analysis of possible power generation for Maniitsoq shows the accumulated net present value of cost for power generation with a diesel price of 0.85\$/L; capacity factor of 28%; and fuel consumption of 0.25 L/kWh. The other input data are explained in Table 1, and the scenarios are presented in Table 2. The current setup is close to the base case; Maniitsoq has 0.1% renewables in the mix.

4.1.3. Kotzebue

Kotzebue is a coastal and predominantly indigenous community situated in Alaska above the Arctic Circle ($66^{\circ}54' \text{ N}$, $162^{\circ}35' \text{ W}$). The community is a local infrastructure hub with a relatively large airport. Because Kotzebue is a hub with around 3150 inhabitants, its population is relatively diverse and dominated by approximately 70% indigenous people [60,61]. Due to the hub situation, the dominant business sector is services, followed by retail [62]. Manufacturing, construction, and other fields have minor shares in the local economy.

There are six engines of five different sizes, ranging from 0.7 MW to 3.1 MW. The wide range of diesel engines allows the operator to run the engines with an optimal load, thereby enhancing the system's fuel economy [26]. The operator can select the most suitable engine size for the forecasted energy demand. One of the engines is a two-stroke engine that can compensate for changes in energy production from the wind turbines. The wind farm was constructed in two phases. During phase one, starting in 1997, 17 wind turbines with 66 kW were added in stages. During phase two, in 2008, two 900 kW wind turbines were added to the wind farm. The wind farm is connected via battery storage. A lithium-ion battery with a capacity of 1.2 MW allows intermittent energy storage to shift the energy from windy to calm periods throughout the day. When the battery is fully charged and the wind farm supplies more electricity than the community needs, a water heater is installed at the hospital as a dump load. The hospital was selected because it is a major consumer of hot water that is usually heated by burning diesel. An additional electrical heating element of 450 kW in the water heating system uses excess electricity to heat water. In this way, electricity is not wasted: on the contrary, it is possible to save fuel for the purpose of heating water [26].

Several small-scale solar installations have already been installed in Kotzebue [26]. PV may be an excellent option for inclusion among various renewable energy resources. Owing to the area's flat terrain, hydropower will not be considered in the case studies.

Figure 5 illustrates a case that differs slightly from the previous two case studies, with cost savings increasing with higher penetration levels. The break-even range is narrow—between 4 and 19 years—owing to high fuel costs. The shortest time to reach break-even is in scenario IV low wind with four years. The longest time to reach break-even of 19 years is in scenario III mid PV. Moreover, the input data reveal that the diesel price is six cents higher per liter than in Maniitsoq. The higher diesel prices account for significant operational cost savings, even in the low-penetration scenarios. Fuel consumption declines in response to increased renewable energy penetration levels, and cost savings will be achieved compared to the base case.

The results show that PV scenarios I and II have approximately the same cost savings over the observed period of 30 years. The cost savings of scenario II are more significant than the cost savings of scenario I. Nonetheless, the cost-saving advantage is equalized by higher initial investment costs and the repurchase of batteries. The low-penetration cases in scenarios I and IV have a significant impact on the cost savings of the energy mix. The cost savings of scenario IV are even higher at approximately the same investment cost as scenario I, making wind the more economically feasible low-penetration option. For the medium-penetration scenarios II and V, some cost reduction can be seen. Similar to the low-penetration scenario, wind scenario V can achieve greater cost savings.

The 'medium wind' penetration case is currently in operation, and significant cost savings are observed. For energy security, it would be interesting to further develop electricity generation using PV instead of only increasing the wind farm. This type of diversification would improve energy security over the months with daylight. The 'high wind' case is the only high-penetration case analyzed for Kotzebue, since PV and hydro are not suitable for the location. The 'high wind' case shows a significant cost-saving effect, with acceptable higher investment costs.

Figure 5. Scenario analysis of possible power generation for Kotzebue shows the accumulated net present value of the cost for power generation with a diesel price of 0.91\$/L; capacity factor of 17%; and fuel consumption of 0.28 L/kWh. The other input data are explained in Table 1, and the scenarios are presented in Table 2. The current setup is close to scenario V; Kotzebue has 18% renewables in the mix.

4.2. Social Impacts

4.2.1. Investment and Energy Costs

Unemployment and social challenges are widespread among Arctic communities, and jobs are often seasonal, part-time, or temporary [63–65]. The high incidence of unemployment can lead to limited tax revenue for communities, which, in turn, limits these communities' public investment potential. A review of the literature and interviews conducted in the three case study communities highlighted the Arctic communities' limited financial resources. These tend to be spent on projects that directly impact communities' overall social well-being [1,66]. Such projects include repairing damaged infrastructure, such as old sewage lines, or community buildings, such as fire stations or first-aid stations. Interviews and data gathered in the three case studies suggest that investment in energy infrastructure is often not the priority because it affects society over a longer time scale, and more immediate concerns relating to economic and social challenges tend to take precedence. This is often the main explanation for the use of outdated electricity generators among Arctic communities [10]. Investment in new diesel generators has several advantages and disadvantages for communities. Modern diesel generators have a better fuel economy with lower emissions, and it is easier to integrate a larger share of renewables into the system [32]. Moreover, the old diesel generators usually require more maintenance, and the operational costs are higher. All these aspects would support new diesel generators and have a positive impact on the communities. However, modern diesel generators use more complex technologies to obtain the aforementioned positive effects [17]. Small com-

munities struggle to find and maintain skilled workforces to operate complex technological systems [17]. In addition, staff turnover at power plants tends to be high [17].

Renewable energy sources can positively impact remote Arctic communities. One significant benefit is reduced energy costs, as witnessed in Kotzebue [30]. The cost-saving effect may be delayed in coming to fruition, depending on the financing of the integration of renewables. Another benefit that is not directly visible is enhanced energy security due to the diversification of primary energy sources and increased energy independence [67]. Energy independence results from the use of local energy sources. As stated in the introduction, fuel imports are critical for remote Arctic communities' energy supply. Local energy sources reduce the need for imported fuel. A positive side effect of integrating renewables and the resulting reduced fuel use is the reduced emission of greenhouse gases and particulate matter.

4.2.2. Social Acceptance

In all three case studies, renewable energy can contribute to cost savings with respect to energy generation. It is however not sufficient to consider the technical possibility, feasibility, and cost savings in introducing renewable energy; in terms of the financial aspects, it is also essential to consider the remote Arctic's unique economic character. The Arctic economy is a mixed economy, and traditional harvesting contributes significantly to many communities' material well-being and livelihoods. The mixed economy is defined by Wolfe and Ellanna [63] as production within the community that 'is a combination of fishing, hunting, gathering, and trapping for local use, and remunerative employment activities such as the commercial sale of fish, seasonal wage work, commercial fur trapping, and cottage industries.' It is important for locals in a mixed economy to be able to participate in the traditional lifestyle of hunting, fishing, and berry picking, as the region's indigenous people are accustomed to living off the land [68]. This would suggest that energy affordability becomes a particularly important issue for locals, allowing them to better economize on often scarce financial resources. Monetary income tends to be low in many remote Arctic communities; poverty and unemployment are often shared issues [64,65]. Owing to the subsistence lifestyle, the available money is limited, and this must be considered with respect to the affordability of energy. The burden of electricity costs can be significant; for example, in Alaska, most remote communities spend up to 10%—in some extreme cases, even up to 35%—of their net income on electricity [69]. Renewable energy sources may offer a means of reducing the burden of electricity costs. Moreover, a subsistence lifestyle characterized by a strong connection to the land may function as another supporting factor in energy transition. The interviews demonstrated that the inhabitants wanted to keep their food sources vital and healthy. Therefore, renewables may play an essential role.

It is also essential to analyze the social acceptance of such a project. Renewable energy technologies may have large footprints and may require land for reservoirs, PV arrays, or wind turbines. Therefore, it is essential that subsistence grounds are not affected by energy infrastructure placement [17,70]. A central problem is closely related to subsistence lifestyles and how energy technology will affect wildlife [71]. This concerns installation outside of the community, such as wind turbines, hydropower, and larger PV arrays. If it is close to the community, it is unlikely to be a hunting ground. Nonetheless, it is critical to include the impact on wildlife and hunting in the assessment to define a suitable location for renewable energy technology. For hydropower, it is vital to ensure fish migration. A minor concern—not frequently mentioned—is related to the reliability of new technologies. The interviews showed some worries that the technology is not suitable for harsh environmental conditions [70]. This is often related to a negative experience in the early adoption phase of renewable energy technologies [70,72].

4.2.3. Interaction between Society and Energy Systems

The interviews conducted as part of the case studies revealed a general acceptance of renewable energy technologies. People generally expressed positive attitudes toward

renewables across the different groups included in the interviews. The extent of acceptance inevitably varies; for example, large consumers are more concerned about the development of energy costs. The acceptance is often based on the positive experiences of significant energy cost reductions, which they have seen in communities with a substantial share of renewables [27,30]. The desire for reduced energy costs is a driving force for the social acceptance of renewables. Of course, concerns persist in relation to renewable energy technologies, such as whether technology will resist the harsh climate or whether it will impact hunting grounds.

A non-diverse field of business may be observed in the three case study communities. Fisheries form a significant part while tourism is emerging, and sometimes extractive industries are located in close proximity to communities. Fisheries foster several supportive businesses, such as food processing plants and workshops, and maintenance of boats and other machines. This industry results from a harvest of approximately 10,000 tons of fish in Maniitsoq and over 114.8 tons in Kotzebue [73,74]. Longyearbyen's fishing industry is more limited, although fish are caught in abundance in the sea around Spitzbergen [75]. Construction and building-oriented companies are also limited in Longyearbyen. A slowly developing tourism sector was observed in Longyearbyen, while Maniitsoq receives a few cruise ships each year. [76]. Extractive industries play an essential role in the Arctic; for example, in Kotzebue, a connection with the Red Dog mine is evident. Tax revenue from the mine is allocated among the area's communities via the Northwest Arctic Borough's Village Improvement Fund [66]. In Maniitsoq, plans are underway for a mega mine [77], which could alter the community's demographics and generate different energy demands. The local industry and offices have an energy demand throughout the course of the day that aligns well with PV's energy supply curve, peaking around noon. For residential purposes, peak demands occur in the early morning and evening.

The interviews and observations in the three communities demonstrate that local policy aims to reduce electricity consumption. Therefore, the efforts to improve public buildings and infrastructure may be summarized as follows. Identifying large electricity consumers and finding more energy-efficient solutions represent a good starting point. Lighting requires large amounts of energy, particularly during the wintertime, when no or limited sunlight is available. Some streetlights have been changed in the studied communities, from conventional models to low-energy consumption LED streetlights in many cases [78,79]. In public buildings, light is also emitted using LED technology, if possible [78,79]. Smart home technologies can help to further reduce energy consumption. Lighting systems can be controlled according to demand, reducing the amount of energy wasted by switching off lights if they are not needed [79]. Electronically controlled pumps and ventilators with linear speeds can meet the demand better than pumps and ventilators, which have different speed steps. With linear speed pumps or ventilators, electricity consumption is optimized to use only the required amount of electricity, because the next highest step is not used. A slightly higher speed would release more warm air than required for a ventilation system or pump more hot water than necessary through space heating [79]. The aforementioned are examples of actions that can potentially minimize the use of electricity in Arctic communities, which, together with increased harvesting of renewable energy sources, can reduce emissions and, in some cases, reduce risks and overall energy costs for the region's inhabitants.

In summary of the main results, the overarching research question of whether renewable energy resources may be a feasible option that can help remote Arctic communities can be answered: in most cases, renewables are already a cost-competitive alternative to the currently predominantly used diesel. Nevertheless, the study has demonstrated that no universal solution can be implemented in all communities, and the optimal solution can vary between places. An implementation strategy, which includes all involved groups, will be necessary for successful energy transition.

5. Conclusions

This research studied the technical and economic feasibility of different renewable energy options for three selected case study communities in the Arctic. The case study communities showed the availability of wind and PV in all cases. The availability of hydropower depended on the local situation and it was not available in Kotzebue owing to the given terrain. The results answer the main question about feasibility and demonstrate that renewable energy sources can offer a cost-competitive alternative to fossil fuels in remote Arctic areas with high fuel prices. Expected increases in fossil fuel costs will make the installation of renewable energy technologies even more cost efficient. Moreover, CO₂ taxes may function as catalysts in the acceleration of the energy transition. A problem for the integration process of renewables in remote grids is the high investment cost, as the case studies have indicated. CO₂ taxes could be used to fund subsidies to make renewable energy projects more cost-competitive, although further investigation is needed in that area. Environmental aspects and social acceptance can create issues for a transition process. The study has demonstrated that renewables can be beneficial for Arctic communities. All three analyzed cases demonstrate that renewables are cost-competitive relative to the base case of 100% diesel. The diesel generators in many Arctic communities are often outdated and require replacement, which brings a further competitive advantage to renewables. It is advisable to use the opportunity presented by an unavoidable generator replacement to integrate a proportion of renewables. The transition process could be accelerated if the investment costs were reduced with various potential support schemes. In some places, such as Greenland, the electricity price is subsidized. The allocation of those subsidies toward renewables can lead to a reduction in electricity generation costs. The case studies demonstrate that no universal solution for all communities exists, and that renewable energy technology must be tailored to each locality's specific needs.

The results indicate that it is advisable to transition to renewable energy technologies rather than continue to invest further in diesel technology as a primary energy source. Renewables will make communities more energy-independent and robust against fuel price changes. This research has addressed the question of whether locals are likely to accept renewable energy technology by indicating that renewables are widely accepted among local inhabitants, but technological acceptance levels and preferences vary. Nevertheless, locations must be carefully selected in close cooperation with local inhabitants to ensure that sacred places and hunting grounds are respected and preserved.

Under the described circumstances of limited budgets, skilled workforce limitations, and outdated diesel generators, the transition toward more renewable energy resources poses several challenges. The consumer's burden, created by electricity costs, can be as high as 35% of net income. Renewables can help reduce the consumer's cost burden over a longer term. Such communities' financial struggles to provide sufficient financial funding to cover the initial investment cost is a key problem that must be solved with a good implementation strategy. For communities with high electricity prices, governmental support could help overcome the initial investment problem. Moreover, it would help break through the path of dependency established in relation to diesel in recent decades.

This research has presented a methodological approach to analyze energy options for remote Arctic communities. This may support communities in their first steps toward successful energy transition. The next recommended step is the development of an implementation strategy for renewables in Arctic communities. An exemplary implementation strategy should not focus entirely on the technological aspects, such as which components are needed to install the system, generate electricity, and operate it stably; a good transition strategy should also concentrate on the techno-economical, socio-technical, and political aspects. Essential factors to consider for a sound implementation strategy include resource availability, potential financing options, available technologies, social acceptance, emissions, supply demand function, policy consistency, and environmental impact.

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