Sustainable Energy Supply in Rural Arctic Areas

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December 2022
Department of Engineering
Reykjavík University

Ph.D. Dissertation

Sustainable Energy Supply in Rural Arctic Areas

Dissertation of 30 ECTS credits submitted to the School of Science and Engineering
at Reykjavík University in partial fulfillment of
the requirements for the degree of
Doctor of Philosophy (Ph.D.)

December 2022

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ISBN 978-9935-539-00-7 Print version
ISBN 978-9935-539-01-4 Electronic version
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Abstract

The dissertation is a collection of the three leading publications, which result from the doctoral research project ‘Sustainable Energy Supply in Remote Arctic Areas - Analysis of resources, technology and policies for developing energy systems’. The research focuses on which energy resources are available in the Arctic and how the various resources can be harvested with different mature energy technology options for remote Arctic communities. Mature energy generation technology means that the operation under harsh and cold climatical conditions is well proven. Furthermore, the current energy situation among remote Arctic communities will be mapped out, with an analysis of which energy sources are used, the share of the different sources, and the energy demand of remote communities. After explaining the different energy generation options and main drivers for using renewable energy in remote Arctic communities, three case studies have been conducted. The case studies examine the viability of a potential energy transition for Arctic communities. The case studies also share some insights from field visits in remote communities on generating electricity with renewables and potential energy saving potentials. The last part elaborates on different integration strategies for renewable energy options. The focus lies on how to finance the energy transition in remote Arctic communities, which can help to structure the energy transition process financially. The dissertation finishes with an overall conclusion on the importance of renewable energy for Arctic communities. The research shows that renewable energy can be vital for remote communities to become more energy independent and lower the energy cost burden.

The undersigned hereby certify that they recommend to the Department of Engineering, School of Technology, Reykjavík University, that this dissertation entitled **Sustainable Energy Supply in Rural Arctic Areas** submitted by **Magnus de Witt** in partial fulfillment of the requirements for the degree of Doctor of Philosophy (Ph.D.) in Engineering.

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date

Magnus de Witt
Doctor of Philosophy

Acknowledgements

I am very thankful for all the support I received while working on my doctoral research. A special thanks should be conveyed to my supervisors, Joan Nymand Larsen, Hlynur Stefánsson, and Ágúst Valfells. I was able to ask them for help whenever any problem occurred during the process of writing the research. They supported me with their inspiration for solving problems related to the actual content of the research or administration-related issues at the university. The journey of my PhD study would not have been possible without the permanent support of my family and friends. The research has as well strengthened my network of friends around the world. The different inputs have always been a considerable contribution and motivation.

Furthermore, I must thank all the people who supported me in obtaining the information needed for the research. Thank you for taking the time to answer my questions and participate in the survey. A special thanks should go to all my interview partners who took the time to meet me in person. I am very grateful for this - without your support, it would not have been possible to conduct the research. During the field study logistical support was vital, and hence a special thanks to my host families in Greenland and Alaska family Brad and Mary Reeves, and in Greenland family Ole and Nikoline Ziemer. I received further logistical support during the field studies in Greenland Nukissiorfiit and Marianne Begstrup. In Svalbard, the Czech research station provided me with accommodation, and the University of Svalbard provided me with research infrastructure. The KOPRI Fellowship has allowed me to broaden the scope of the research and apply some results to Antarctica.

This research project was realized with generous financial support from different sources, for which I am most grateful. It has received significant funding from Iceland Research Fund (Grant Nr. 195846-053), specific funding for field visits, publication, and conference participation from the Landsvirkjun Energy Fund (Grants NÝR-10 – 2019, NÝR-17 – 2020 & NÝR-15 - 2021) and financial support from Reykjavik University. Moreover, the research was awarded some conference and travel funds from the System Dynamics Society and the International Arctic Science Committee.

Preface

This dissertation is original work by the author, Magnus de Witt [1-6]. The work will be presented in the chapters (Chapter 2, 3, and 4). Chapter 2 maps out the electricity generation and consumption of the rural Arctic [4]. In Chapter 3, a feasibility study highlights the potential use of renewables for selected case studies communities [5]. The final Chapter 4 of the core work presents an analysis of energy transition pathways for Arctic communities [6]. Additional work is presented in the appendix (Appendix A, B, and C). Appendix A elaborates on the potential of renewables to improve energy security in the remote Arctic and the political implications [1]. Appendix B highlights the importance of energy security for Arctic communities [2]. Appendix C focuses on the social importance of energy in the rural Arctic [3].

The published papers are:

[1] M. de Witt, H. Stefansson, A. Valfells, Energy security in the Arctic: policies and technologies for integration of renewable energy, Arctic Yearbook 2019, **2019**, pp.189-196.

[2] M. de Witt, H. Stefánsson, Á. Valfells, Sustainable Energy for a Secure and Affordable Energy Supply: An Analysis of Rural Arctic Communities; International Association for Cold Region Development Studies: Oulu, Finland, **2019**.

[3] M. de Witt, Á. Valfells, J.N. Larsen, H. Stefánsson, Dependence On Electricity Among the Inhabitants of the Rural Western Arctic. Kunstkamera 7, **2020**, pp. 25–35, doi:10.31250/2618-8619-2020-1(7)-25-35.

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[5] M. de Witt, H. Stefánsson, Á. Valfells, J.N. Larsen, Availability and Feasibility of Renewable Resources for Electricity Generation in the Arctic: The Cases of Longyearbyen, Maniitsoq, and Kotzebue. Sustainability 13, 8708, **2021**, https://doi.org/10.3390/su13168708.

[6] M. de Witt, H. Stefánsson, Á. Valfells, J.N. Larsen, Simulation of Pathways Toward Low-Carbon Electricity Generation in the Arctic. Sustainability 14, 15311, **2022**, https://doi.org/10.3390/su142215311.

Contents

List of Abbreviations

CHP	Combined Heat Plants
CO2	Carbon Dioxide
DOE	US Department of Energy
EIA	US Energy Information Administration
GRP	Gross Regional Product
IEA	International Energy Agency
IPCPC	Intergovernmental Panel on Climate Change
IRENA	International Renewable Energy Agency
kW	kilo Watt
kW/h	kilo Watt our
kWp	kilo Watt peak
MG	Micro-Grid
NOx	Nitrogen Oxide
OECD	Organisation for Economic Co-operation and Development
PM	Particular Matter
PV	Photo Voltaic
REF	Renewable Energy Fund
RPSU	Rural power System Upgrade
SD	System Dynamics
SDG	Sustainable Development Goal
USD	US Dollar
VoLL	Value of Lost Load

1. Synopsis

1.1. Background

The Arctic can be defined in three ways, by the Arctic Circle (66°33′ N), the Arctic tree line, and the 10°C summer isotherm temperature line [1]. The Arctic ecosystem is sensitive to change; even small changes in the ecosystem can significantly affect the local climate, even if the climatic conditions are cold and harsh. The globally increased CO2 levels has led to a rise in temperature[2], and these higher temperatures might lead to changes in weather patterns. Climate observations show that climate change has a significant impact on the Arctic environment. The loss of snow and ice in the Arctic can lead to further acceleration of the global climate change because ice and snow can reflect up to 70% of solar radiation [3]; without ice and snow, the surface of the earth absorbs more heat. It is observed that the temperature increases up to three times faster in the Arctic than elsewhere on the planet [4,5]. The Arctic people have a close connection to nature due to spiritual reasons and as sources of food [6]. Many Arctic inhabitants live from hunting and fishing. Most of the Arctic and Sub-Arctic communities are located very remotely. The remoteness makes it impossible for most communities to connect to a continental electricity grid [6]. That means the communities must generate the electricity locally and have no option to trade electricity if needed. Literature shows that fossil fuels, mainly diesel, are used in 80% of remote communities [7]. The use of diesel leads to several impacts, which can be categorized into socioeconomic and environmental effects.

One of the most severe socioeconomic impacts related to the use of diesel is its transportation. The harsh Arctic climate conditions make the shipment risky. In general, two options can be found using trucks and ice-roads – frozen rivers, if the ice layer is stable enough - the second option is to ship the fuel on barges if the rivers are navigable or the community is at the shore. For both options, it is difficult to schedule a shipment within the short timeframe available. Especially the ice-roads become more unstable due to climate change [7]. That leads to a higher risk of transportation accidents [8].

Another problem is that if not all the fuel for the next year can be delivered during the short timeframe, it has to be flown to the communities, which is extremely expensive. All of these factors lead to high transportation costs. The transportation cost is one part of the high electricity cost. Other reasons for the high electricity price are the large storage needed and the remoteness, which makes every inspection and spare part delivery expensive. Reliability is vital in the Arctic since electricity is essential for health and well-being under harsh climate conditions [9]. The noise of the diesel generators can be a disturbing factor in remote and quiet communities.

The environmental impact of diesel use is mainly related to greenhouse gas emissions, like CO2 and black carbon [10,11]. Both are a significant component of climate change, but black carbon has a unique role in the Arctic. After its lifetime as an aerosol, if the particular matter settles down on ice or snow [12], the small particles absorb solar radiation, and that increases the meltdown of snow and ice. Another impact is more related to transportation and storage. Sometimes accidents happen during the transport, or storage leaks can result in diesel spills [13,14]. These diesel spills can lead to land degradation, which can be traced even several years after the impact. Furthermore, toxins from the diesel spill can enter the food chain [6].

As well as the environmental impact related to the use of diesel, remote Arctic communities are facing a major issue resolution from power generation with diesel. The already described complex transportation of diesel to remote places comes along with high fuel costs [7]. Using expensive diesel for electricity generation results in high electricity production costs [8]. As long as no subsidies for diesel powered electricity generation or electricity are in place, the consumer has to pay high electricity prices. The increased electricity prices occur in a region where unemployment and poverty are common [15]. This cost burden for inhabitants of remote Arctic communities is a significant reason for conducting the following research. The subsequent analysis will determine whether renewables can help overcome the cost burden

1.2. Motivation and Aim

The belief that renewables can present an opportunity to provide cheap and secure electricity with an affordable environmental and social impact under the harsh conditions of remote Arctic communities was the driving force for conducting the following research. The social impact is essential since a traditional lifestyle is common among indigenous inhabitants of the Arctic. In the preliminary study phase of the PhD project, a gap between energy generation technology development and energy policy for Arctic communities was identified. We believe that the missing link between energy technology development and energy policy is a well-structured energy integration process. To ensure that there is a gap in real life and that there is a need to fill the gap an Arctic Circle Assembly was used to communicate with involved people. After that experience, it was certain that there is a need to study the energy transition process and maybe help to lower the cost burden in remote Arctic communities.

The overarching question of the conducted research is ‘can renewables provide affordable energy to remote Arctic communities?’ Therefore, it should be proven that the electricity price of renewable energy technologies can be competitive with diesel-generated electricity. Even for remote Arctic communities with harsh climatical conditions, where the construction of infrastructure is more complex and expensive [16] the integration of renewables could contribute to lowering the cost burden of energy-related costs. Lowering the cost burden would be a small contribution to improving the well-being of remote Arctic communities. It can be seen that technical solutions to use renewables already exist and are in use as explained in detail in the first paper. Nevertheless, there is still potential to improve and adapt the technology for Arctic conditions.

To answer the overarching research questions with which the research has started a set of underlying questions had to be answered to fill knowledge gaps. One major gap identified is the integration of renewable energy into remote communities. This is a gap between energy generation technologies for remote Arctic conditions and energy policy in the Arctic. Therefore it should be answered ‘which integration strategies can be used to implement renewable energy into remote communities, and how can the integration be financed?’ To be able to analyze the structure of a potential energy transition process, it is essential to know the current energy situation in remote Arctic communities. Since the existing literature did not provide an overview of the whole western Arctic, the research started with data collection and mapping the Arctic communities' current energy landscape. Therefore a set of questions had to be answered. ‘How is the current energy situation in remote Arctic communities?’ ‘Which energy source is available?’ These two questions are answered in the first paper. In the beginning, it was stated that we believe renewable energy can be cost-competitive with energy generated by diesel under remote Arctic conditions. This hypothesis has to be proven. Therefore, the second paper answered the question ‘can renewable energy be a feasible option in the Arctic?’. For the successful integration of renewables, we believe it is essential to have a well-balanced integration strategy. The integration strategy should be well balanced between the different stakeholders. Therefore, the question ‘how to finance the energy transition, and which financing strategies can be useful?’ is answered in the third paper. The underlying questions must be answered to create renewable energy integration strategies. The integration strategies of renewable energy can be analyzed and help answer the overarching question. The overarching question of whether renewable energy can provide secure and cheap electricity to remote Arctic communities is answered in the final conclusion of the dissertation.

In a broader sense, this study can help remote Arctic communities to become more energy independent and self-sufficient. Renewable energy can help remote Arctic communities to be no longer be dependent on imported fuel. Furthermore renewable energy might help to become independent from subsidies which are in some places are introduced to lower the cost burden by reducing the electricity prices. Moreover, the energy transition should be aligned with the opinions of the inhabitants of the community. It is important to integrate the locals into the transition process so that the solution fits their lifestyle and that the community has the capability to operate and maintain the new infrastructure. The environmental impact of the new infrastructure should be in a responsible manner.

1.3. Structure

The following thesis is a collection of the leading publications which were written during the PhD research. The first publication, ‘Energy recourses and electricity generation in Arctic areas’ sheds light on the situation of current energy supply in remote Arctic communities. Furthermore, the article elaborates on possible energy generation technologies for Arctic communities. The second publication, ‘Availability and Feasibility of Renewable Resources for Electricity Generation in the Arctic: The Cases of Longyearbyen, Maniitsoq and Kotzebue’ builds on the results of the first publication. Data that has been collected during field visits in the three communities is the basis for elaborating on the feasibility of different renewable energy scenarios in the case study communities. The third and final paper, ‘Strategies to change Arctic electricity generation to a low CO2 level’, combines the findings of the previous publications. The article presents an abstract simulation that can be used to simulate different integration strategies for renewables in Arctic communities and shows the effect on the electricity market.

Besides the main research stream that resulted in the main publication, there have been some other publications. An important side project was the analysis of energy security in the Arctic. The main work on energy security in the Arctic was published in the Routledge Handbook as a book chapter ’Energy recourses and electricity generation in Arctic areas’. The ISCORD conference proceeding ‘Sustainable Energy for a Secure and Affordable Energy Supply: An analysis of rural Arctic communities’ focuses on the impact of renewables on energy security in isolated energy systems. Another publication on energy security was published in the Arctic yearbook 'Energy security in the Arctic: Policies and technologies for integration of renewable energy' with a focus on policy and technology to improve energy security with the help of renewables in remote Arctic communities. The often discussed energy poverty in remote Arctic communities has led to the Kunstkamera journal "Dependence on Electricity among the Inhabitants of the Rural Western Arctic" publication. The article discusses the cost burden of conventionally generated electricity and the importance of secure and cheap electricity for remote Arctic communities.

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2. Paper 1

Energy recourses and electricity generation in Arctic areas

2.1. Introduction

The Arctic can be defined according to the Arctic Circle (66°33’ N); the Arctic tree line; and the 10 °C summer isotherm temperature line [1]. Arctic inhabitants are exposed to cold and harsh climactic conditions, and the Arctic ecosystem is sensitive to change; even small changes in the ecosystem can have significant effects on the local climate. For example, the global increase in CO2 levels has led to a rise in temperature [2], and these higher temperatures can lead to changes in weather patterns. Climate observations show that climate change happens first to-and has the greatest impact on-the Arctic environment. Climate change in the Arctic has led to loss of snow and ice, which further accelerates global climate change because ice has the capability of reflecting up to 70% of solar radiation [3]; without such ice the surface of the earth absorbs much more heat. It is observed that the temperature increases two to three times faster in the Arctic than elsewhere on the planet [4,5].

The area above the Arctic Circle covers 20 million km2 [6], of which about three quarters is covered by the Arctic Ocean [7]. The remaining quarter, around 6 million km2 is land mass. The population of the Arctic, which can be geographically defined in different ways as pointed out before, is very scattered and inhabited by approximately four million people [8,9]. Low population density has led to the scattered distribution of settlements, and with settlements often disconnected by roads and remotely located. This remoteness, along with long distances between Arctic settlements, adds complexity to infrastructure projects in the far north in terms of planning, transportation, implementation, operation, and maintenance [10-12]. This is also true for electrical infrastructure projects, and adds to the high cost of infrastructure in Arctic communities. In temperate areas, overland electricity lines follow the roadways. In the absence of roads, introducing an electricity grid becomes an even greater challenge, and this is the reason why many Arctic communities use an islanded electricity grid. Islanded electricity grids have no connections to continental electricity grids. Sometimes, however, neighboring communities build linkages between them. The isolation of electricity grids, which often rely on a single generator station and a single transmission line, makes the grids more vulnerable and reduces energy security. Diesel is the primary energy resource in most settlements. The transportation of diesel to remote settlements also adds considerable risk, uncertainty, and cost to fuel delivery. Depending on the location, transportation is undertaken using barges, ice-roads, or plane. Energy security is an important topic and critical challenge in isolated and remotely located Arctic communities because electricity is vital for health and safety, in addition to being used for entertainment, and to improve productivity [13]. Blackouts in cold climates can quickly lead to life-threatening situations [14,15]. The energy demand fluctuates over the year. It can be observed that the energy demand is highest over the winter due to increased demand for heating and lightning purpose [16]. For example, electricity is used to prevent waterpipes from freezing and for space heating. In addition to the seasonal demand variation an intra-day variation can be observed, depending on the on the local industry. Some energy sources, such as diesel and hydro with a reservoir, can in most cases easily be adjusted to variations in demand, but others are not as flexible, such as wind and photovoltaic. For the less flexible energy sources electricity storage can be used to balance the variations between demand and supply [17]. With the introduction of wind and photovoltaic to an islanded electricity grid, variations on the supply side can be expected due to the varying availability of the energy source [18]. Variations on the supply and demand side of the electricity system can lead to over dimensioning of the generator or back-up capacities to ensure a secure electricity supply at any time [19]. Based on published data, in addition to new data collected for this review, this paper aims to improve our understanding of electricity infrastructure, and it provides an overview of the current fossil-fuel based and renewable-energy based electricity generation and supply in the Arctic and Sub-Arctic regions of Alaska, Canada, Greenland,

and Norway. A specific aim of this study is to answer the following question: “Which sustainable resources are available and with which mature technologies can these resources be harnessed? Moreover, the potential socio-economic impacts of renewables in the Arctic, the importance of uninterrupted availability of electricity in the Arctic, and the burden of high electricity prices for cost of living will be discussed. The paper aims to contribute to a further understanding of how the current electricity supply systems will facilitate the transition towards increased use of more sustainable energy systems based on renewable energy resources.

2.2. Methodology and data collection

This research is based on primary and secondary data, as illustrated in Fig. 1. The literature review began as a scoping review to provide an initial overview of the subject and to identify knowledge gaps [20]. The result of the scoping review is an overview of electricity generation, transmission, and consumption in the Arctic, including information on the natural, political, and economic environment. The scoping review has provided the backbone for a more detailed review of the literature. Two overarching sections were identified from the scoping review: energy matters and Arctic issues. These two subjects comprise several subareas such as energy generation, energy security, energy technology and micro grids, Arctic environment, Arctic policy and Arctic economics (see Fig. 2). The aforementioned areas have provided the starting point by which a snowballing literature review can go into greater depth and detail. The snowballing review was organized in a backwards moving process, meaning that the references of a paper were evaluated and; if the paper was relevant and available, then corresponding papers were also included in the review [21]. This was undertaken through several iterations until all relevant data for the database were collected, or until the literature review reached a dead end, meaning the gained information was not relevant for the scope of this research.

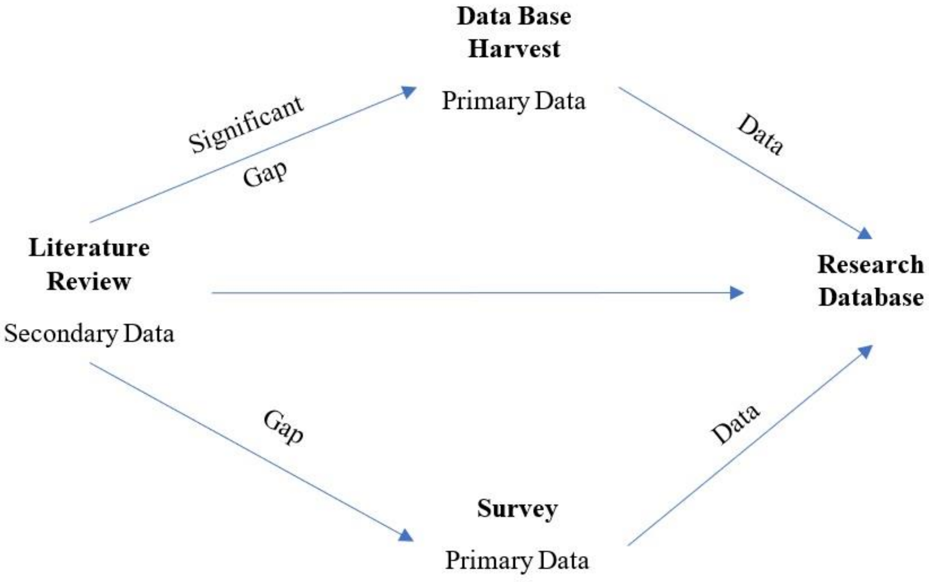


Figure 1. Methodology design for data collection. The first step involved a review of the literature. Depending on the gap of knowledge, which is an incomplete dataset, and due to availability of information identified in the review, two other methods were also used: surveys, for smaller information gaps; and a database harvest, for larger information gaps.

The results of the literature review, database harvest, and surveys were collected into a single database. Collected data on the studied regions were then processed as shown in Fig. 1 and divided into three categories: detailed data, basic data, and identified data, as represented in Table 1. The ‘detailed data’ category represents communities whose electricity generation technologies, installed capacity, and the resulting generation, is known. This data category is the most valuable for research because it contains the highest information density. The capacity factor for a given installation was calculated and analyzed to verify the electricity generation data. In the case of the capacity factor exceeding 80%, a flaw was considered among the related data, since the average capacity factors from the EIA (US Energy Information Administration) show a capacity factor below 80% for most energy sources [22,23]. A closer look at the particular dataset shows that, if the data is reliable, it should be included in the ‘detailed data’ or ‘basic data’ category. The ‘basic data’ category represents datasets on communities with known electricity generation technologies, but which provided inconsistent information regarding performance, installed capacity, or the resulting generation. The ‘identified’ category includes data on communities that have been identified as existing in rural unconnected areas, but about which no information regarding electricity generation technology or performance could be found.

After the completion of the literature review, several datasets within the ‘basic data’ category were identified. The next step was to collect primary data on incomplete datasets. Different approaches were used to collect primary data, and data were collected by contacting corresponding energy authorities and energy companies, either by getting direct access to their databases or via their replies to inquiries. In the case of Greenland, Nukissiorfiit, Greenland’s national energy company, provided access to its databases and the required information on most Greenlandic communities. In Alaska and Canada, however, numerous small utility companies provide electricity to different communities, and therefore gaining direct access to their data was not possible. Inquiries were then sent out to these companies with specific questions that concerned these missing data; however, the response rate to these surveys was low, at approximately 20% (see Table 2). A higher response rate would have provided more detailed data.

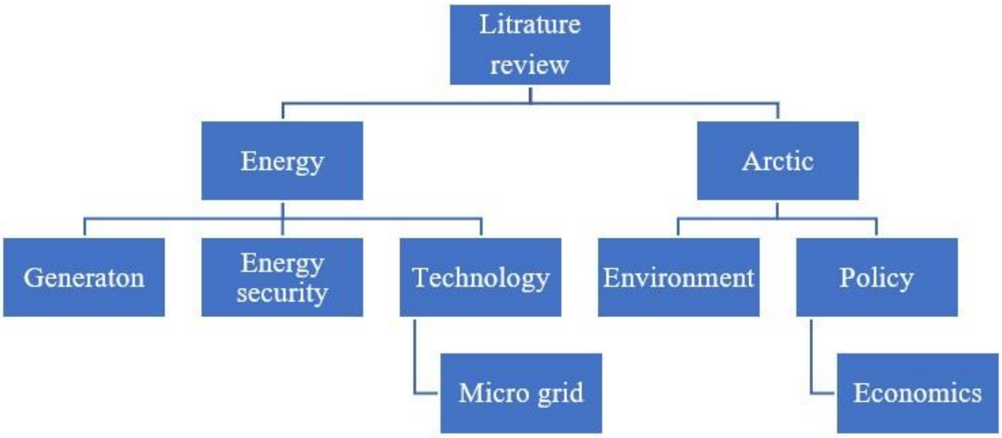
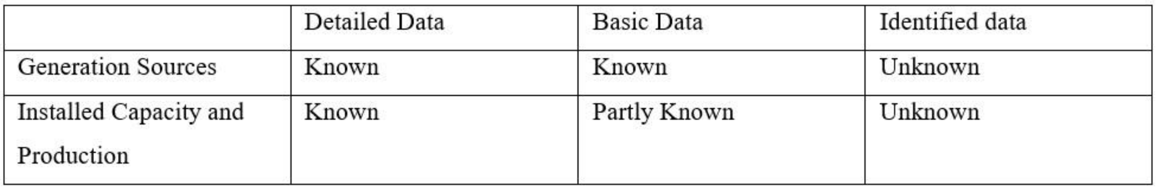


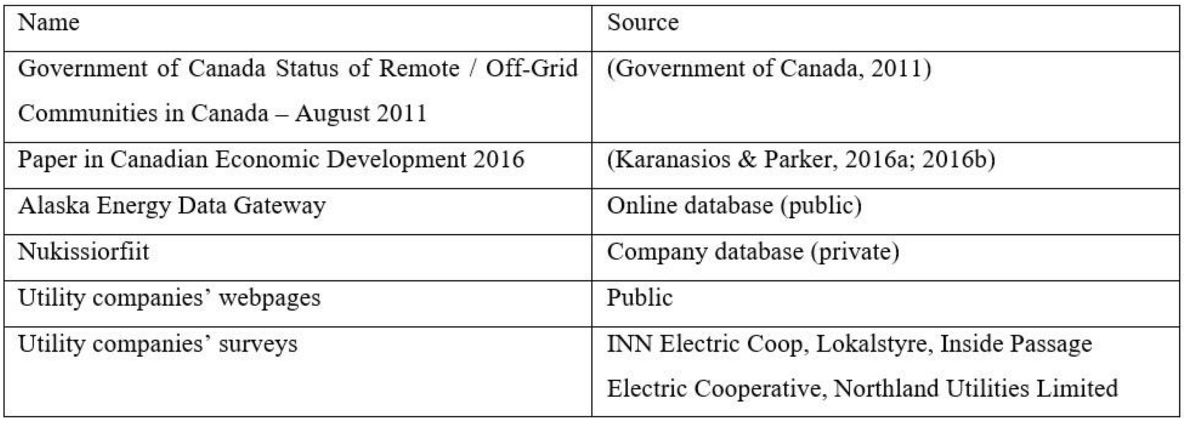
Figure 2. Structure and topics of the scoping literature review

Table 1. Data density for electricity production and consumption, which shows how much information a data set can deliver. The three categories are selected in accordance with data density.



	Detailed Data	Basic Data	Identified data
Generation Sources	Known	Known	Unknown
Installed Capacity and Production	Known	Partly Known	Unknown

Table 2. Main data sources for this research



Name	Source
Government of Canada Status of Remote / Off-Grid Communities in Canada – August 2011	(Government of Canada, 2011)
Paper in Canadian Economic Development 2016	(Karanasios & Parker, 2016a; 2016b)
Alaska Energy Data Gateway	Online database (public)
Nukissiorfiit	Company database (private)
Utility companies' webpages	Public
Utility companies' surveys	INN Electric Coop, Lokalstyre, Inside Passage Electric Cooperative, Northland Utilities Limited

Various private small-scale power-installations are not identified in this study. This is because such power-installation are islanded private solutions that have no interactions with local electricity providers. According to sales estimations, however, a total installed capacity of small-scale solar panels in Greenland is approximately 2.5 MWp [26]. Another limitation to this review is the age of the collected data, which may have resulted in inaccuracies regarding data on electricity prices. This is because some of these electricity price data are from 2014, when the price of crude oil fell from 100 USD/barrel to less than 50 USD/barrel [27]. It is likely that this drop in the oil price had an effect on the fuel cost in Arctic communities, and that this resulted in lower electricity prices. For example, in Hoonah, Alaska, the price of electricity fell from 65 USD ¢/kWh in 2013, to 53 USD ¢/kWh in 2018 as the data collection shows.

2.3. Energy technologies and socio-economic impact

2.3.1. Overview of communities and data availability

This study includes 553 remote communities in the Arctic and sub-Arctic areas of Alaska, Canada, Greenland, and Norway. The Russian Arctic was not included because of a language barrier which makes it complicated to access the needed data in a sufficient quality. All communities included in this study are identified in the literature review through databases provided by corresponding utility companies, energy authorities, and scientific reports. The number of communities used is in agreement with other examples in the literature, such as that of Kaufmann, who identified 550 communities [28]. Fig. 3 shows the distribution of communities across the study regions (Arctic Norway, Greenland, Canada and Alaska), while Fig. 4 shows the various locations of these communities.

All accessible data collected from the database harvest and surveys, as presented in Table 2, were compiled in a research database. Table 3 shows the distribution of communities according to those data-availability categories defined in Section 2.2. A majority of the communities included in this study, representing more than 50% are found in Canada, followed by United States with Alaska, which has more than a third (34%) of included communities; Greenland represents slightly more than 10%, while Arctic Norway with Svalbard, represents less than 1% (see Fig. 3).

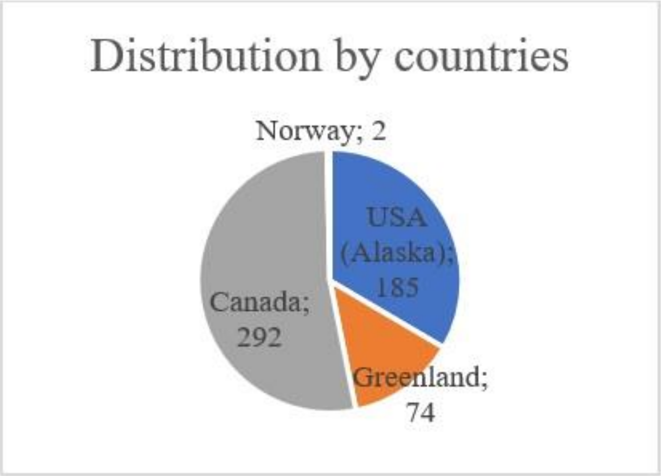


Figure 3. Distribution by countries of detailed data.

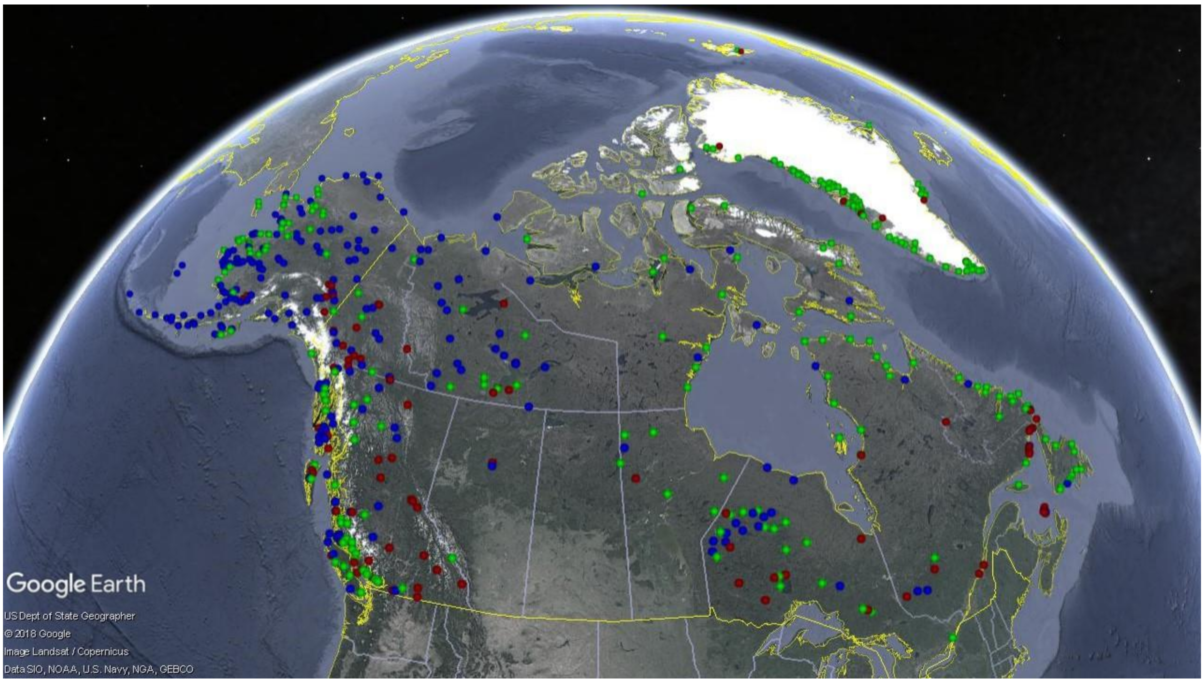


Figure 4. Illustration of the research area according to detailed data (green), basic data (blue), and identified data (red) [29].

Table 3. Communities identified in this research. The communities are sorted according to data density level.

	Detailed Data	Basic Data	Identified Data
Number of communities	243	211	100

2.3.2. Electricity generation and installed capacity

In the remote Arctic the most commonly used energy sources for electricity generation are diesel, followed by several mature renewable energy technologies such as hydropower, wind power, and photo voltaic (PV) power. In Section 2.3.2 the technologies used to harness energy are discussed in more detail.

Up to 79% of Arctic communities included in this study were, at the time of this study exclusively dependent on diesel as a primary energy source, with 6% of communities using hydropower systems, and 15% using hybrid systems for their energy (see Fig. 5). Hybrid systems are those systems that use fossil fuels mixed with renewables [13].

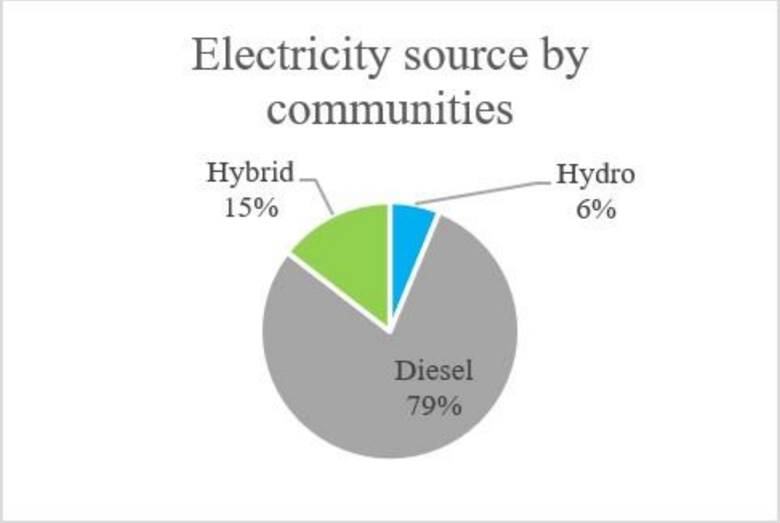


Figure 5. Shows the energy sources for generation of electricity such as diesel, hydropower, or hybrid systems, which are a combination of a diesel generators with non-dispatchable energy resources such as wind and PV power referring to the number of communities. Data used: Basic Data & Detailed Data (gathered by author).

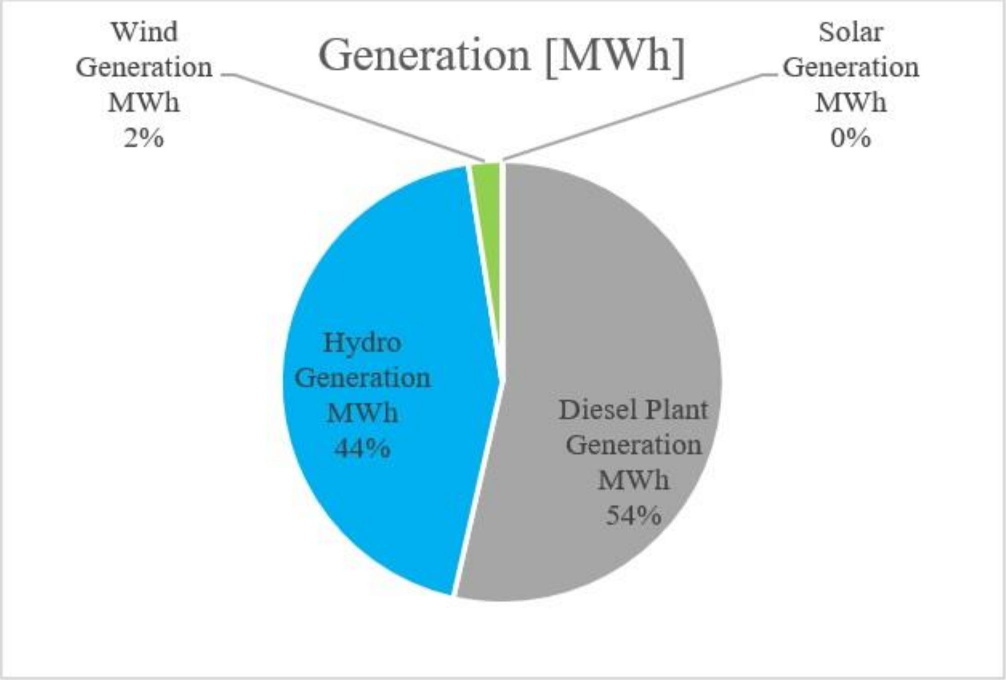


Figure 6. The figure shows how the generation of electricity (in MWh) is divided between diesel generators, wind generators, and generation using hybrid systems. Hybrid systems are systems that combine a diesel generator with non-dispatchable energy resources, such as wind and PV power. Data used: Detailed Data (gathered by author).

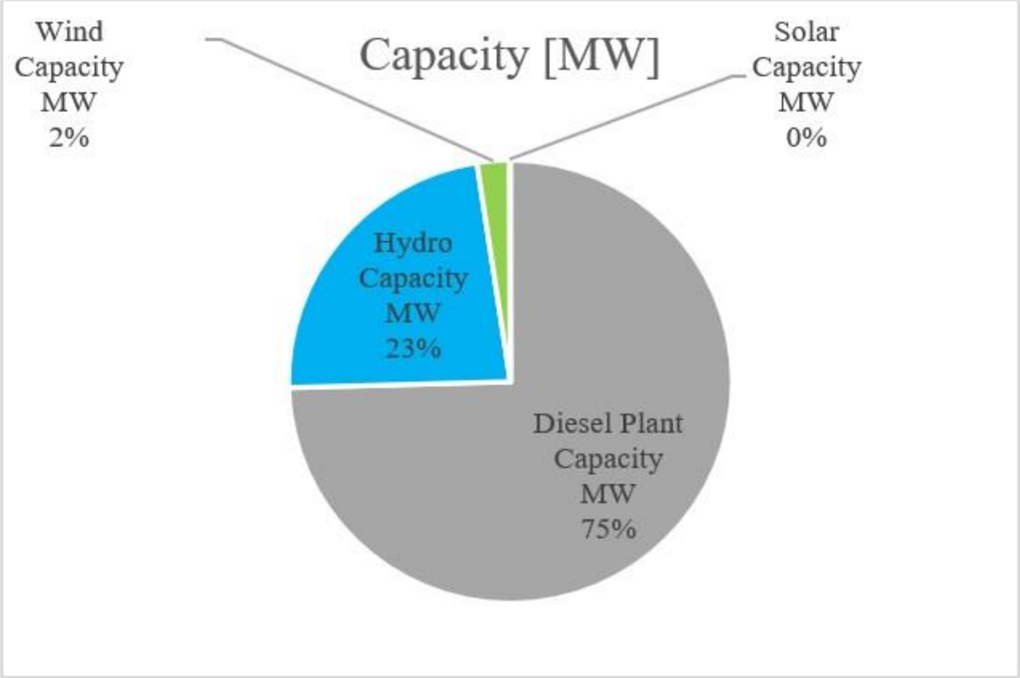


Figure 7. Installed capacity for electricity generation (in MW) divided into diesel plant capacity, hydropower plant capacity, wind power capacity, and PV capacity installed in the Arctic. Data used: Detailed Data (gathered by author).

Consideration of the overall electricity generation data among unconnected Arctic communities reveals that a similar amount of electricity is generated using diesel and hydropower (Fig. 6). Diesel generators are responsible for 54% (~640 GWh) of electricity generation, followed by hydropower plants, which generate 44% (~510 GWh). Other renewable sources, such as wind and PV, comprise only a small portion of the present generation mix, at less than 3%. Compared with the world's electricity production, where hydropower accounted for 16% of electricity production worldwide in 2015 [30], hydropower plays a major role in Arctic areas.

The installed capacity (Fig. 7) shows a clear domination of diesel generator capacity, at 75%, and hydropower capacity, at 23%. These data represent the total installed capacity, no distinction is made between installed capacity for normal use and installed capacity for back-up purposes. Such a distinction is not possible because in small communities it is common to shift between generators so that use is distributed equally among available generators. Other renewables, such as wind and solar power, contribute just 2% of electricity to the installed capacity. Diesel generators are the most commonly used method of electricity generation because they are a well-proven technology, having been widely used over recent decades. Furthermore, diesel generators can work as a back-up source and cold start in mere seconds, and the emergency start in cases of blackouts can be automated [31]. This makes diesel generators very suitable as a back-up energy source as further discussed in Section 3.3.6.

A significant difference exists between installed capacity (Fig. 7) and actual electricity generation (Fig. 6). This major difference relates to the fact that diesel generators installed as back-ups, and primary electricity generation cannot be distinguished from one another. This ambiguity is responsible for diesel generators dominating installed capacity.

Two different types of energy resources are found: dispatchable and non-dispatchable energy resources. Dispatchable energy resources include diesel and hydropower sources, while non-dispatchable energy sources include wind and PV electricity generation. Dispatchable energy sources have the ability to adjust output according to electricity demand. This makes it possible to power an entire grid using only dispatchable energy without the addition of considerable grid-stabilization technology. Comparatively, non-dispatchable energy sources have a commonality in that their output performance can fluctuate in terms of voltage and frequency [32]. This only allows for a low penetration of non-dispatchable energy sources regarding the total amount of electricity generated; of approximately 20-30% [32-34]. Diesel generators can regulate the voltage and frequency for a low penetration of non-dispatchable resources [33]. Concerning those systems that have a non-dispatchable energy fraction above 20-30%, additional regulation equipment is needed to secure a constant voltage and frequency [32]. Such high-penetration systems can attain a fuel saving of up to 70% [32]. This often leads to a mixture of diesel generators being used for a reliable dispatchable load with additional non-dispatchable energy being provided by renewables.

A comparison of installed capacity and size of community among those communities powered by hybrid systems and diesel based system can be seen depicted in Fig. 8. Communities using hybrid energy systems have a slightly higher installed capacity than diesel-powered communities. Hybrid systems are often a combination of diesel with a non-dispatchable renewable energy source [13]. The combination of diesel with wind is common as well as diesel with PV. Hybrid systems need a higher installed capacity due to the fluctuation of the non-dispatchable electricity sources [33]. In most cases diesel generators are of a large enough size that the whole community can be powered using them in the case of renewable electricity being unavailable. This indicates that emergency back-up is not the main purpose of diesel generators in hybrid systems; such diesel generators are used to meet supply shortages and control the frequency and voltage in the grid [32]. It is for this reason that communities who use hybrid systems for electricity generation require a higher installed capacity in relation to their community size. This comparison shows that a higher total installed capacity is needed if non-dispatchable energy sources are to be used in combination with diesel generators. The installation cost of hybrid system can therefore be assumed to be greater due to the higher installed capacity of dual systems.

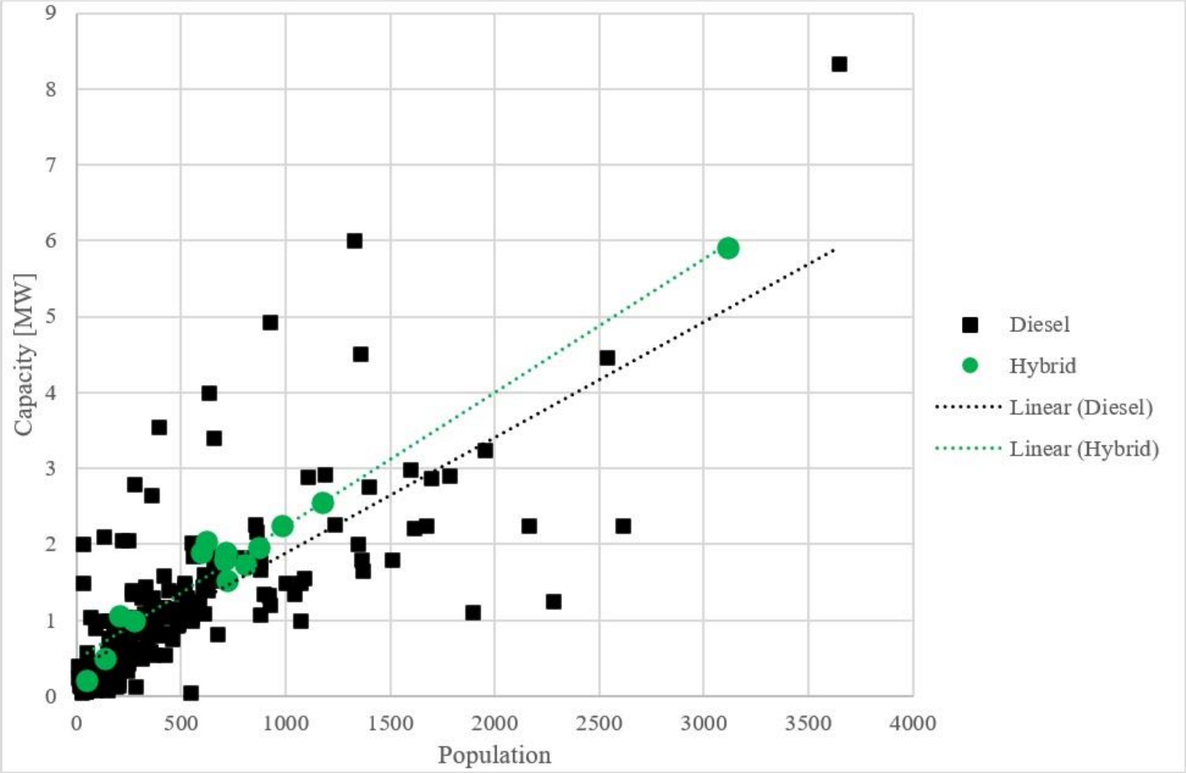


Figure 8. Comparison of diesel (black) and hybrid (green) powered communities. It can be seen that hybrid systems require a greater installed capacity for the same community size. Data used: Detailed Data.

The fuel savings of a hybrid system can be considerable. For a low penetration hybrid system, up to 20% fuel saving and for a high penetration hybrid system the fuel saving can reach up to 70% [32]. Non-dispatchable energy sources such as PV and wind energy can cause fluctuations in voltage and frequency in the electricity distribution system. To even out such fluctuations and provide a secure electricity supply, smart grid components are needed. A smart grid operating in an islanded mode has preferably a peer to peer control, generators use the current information for the control strategy [35]. An intermediate energy storage, such as a battery bank or supercapacitor can act as spinning reserve and even out fluctuations in voltage or frequency [18,36]. The sensors in the smart grid help to manage the distributed generators and the different consumers [35]. In case the primary consumers, residential and industry, cannot take all the electricity generated by non-dispatchable renewable energy sources, the smart grid controller directs the electricity to a secondary consumer [18]. The secondary consumer can be an energy storage such as a battery bank or the electricity can be converted into heat [37,38]. The heat can be used in a centralized manner, with a district heating system or in a decentralized way with a local heating system.

2.3.3. Potential use of different energy sources

2.3.3.1. Diesel

Diesel generators are a proven technology in the harsh Arctic environmental and have been used effectively for several decades [39]. Long-term use of diesel generators has contributed to creating a well adopted infrastructure for their use. Diesel generators are preferred because of their simplicity, and because these generators have the ability to ensure grid stability in terms of frequency and voltage [32]. There are, however, two notable negative issues related to the use of diesel in the Arctic. First, the transportation of diesel to communities involves potentially considerable risks and expenses [12-15,40], with increased transportation cost and higher energy costs for consumers. Shipment of fuel involves ice roads and trucks crossing frozen rivers during the wintertime, and this is heavily influenced by temperature rise, thawing permafrost, as well as the use of barges in the summertime [13]; both options have a short period of use due to the harsh Arctic weather conditions [14]. During this short timeframe, enough fuel for a community’s annual fuel consumption must be shipped in. Second, greenhouse gas emissions, particular matter (PM) such as black carbon and nitrogen oxide (NOx), resulting from the use of diesel have an impact on the local environment [13,41,42]. Black carbon on snow or ice increases the absorption of solar radiation, which leads to faster thawing of the ice and reduced snow coverage [43].

Another risk factor concerning the use of fossil fuels is the possibility of fuel spills during transportation or storage [14]. Oversized storage tanks are needed to supply fuel for small communities for at least a year, and the long term storage can create additional cost [14]. Since diesel is the most common energy source among Arctic communities several incentives have been introduced to make diesel affordable, the high diesel price is the result of the aforementioned transportation constand the diesel prices at the sport market. Different forms of subsidies can be found, including direct subsidization of electricity prices, or indirect subsidization of fuel prices [12,14,15,25,44,45]. To use fossil fuels as efficiently as possible, several diesel power plants can be upgraded to combined heat plants (CHP). These allow for an increase in efficiency from 33 to 45% to around 60e80% by utilizing waste heat [22,23,46]. For example, the diesel power plant in Qaanaaq, Greenland was upgraded to a CHP and subsequently reached an overall efficiency of up to 80% [47]. Section 3.3.3.2 discusses how renewable energy sources in the Arctic can be harnessed in order to reduce greenhouse gas emissions.

2.3.3.2. Hydropower

Research shows that hydropower comprises a large part of the Arctic energy mixture (see Figs. 5 and 6). Even with an installed capacity of less than 25%, hydropower delivers more than 40% of the total electricity generation in the Arctic (see Fig. 7). Although hydropower plants generate a large proportion of the total electricity generated, they have only been installed in a few larger communities. Seven of the ten largest communities in the studied area use hydropower as their main source of electricity generation. he construction of larger hydropower plants results in considerably lower unit-cost of electricity, while the cost per installed kW rapidly increases for small hydropower plants (see Fig. 9). Due to economies of scale, such hydropower plants are often located in a few large communities, or in communities with regional grids.

This study identifies six hydropower plants with an output above 20 MW (see Fig. 10). The high investment cost means that hydropower projects often are impossible options for smaller communities. The average lifetime of a hydropower plant is 50e100 years, and the operation costs are relatively low, which typically results in a payback time of around 20 years [48]. One option might be to create higher electricity demand by introducing industry to the area to increase electricity consumption, thereby securing finances for a larger project. This involves considerable risk but, if successful, can create job opportunities in areas that often have high unemployment rates [49,50]. Such an increased economic activity can however impact the environment in a negative way and therefore, for every individual case the trade-off between environmental impact and economy and society should be carefully evaluated.

Several locations, which have the geographical setting and an interest in hydropower can be observed, mainly close to larger communities. The investigations are at very different stages ranging from basic possibility studies as in Longyearbyen [51]. to more detailed planning studies such as in Maniitsoq [52].

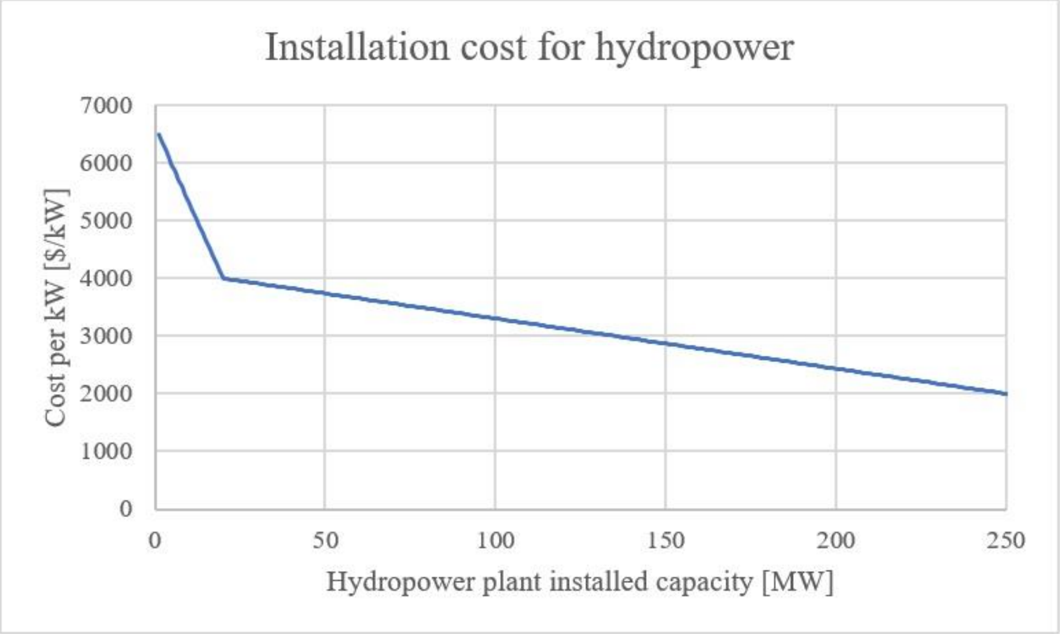


Figure 9. Economy of scale for hydro plants cost per installed kW [48].

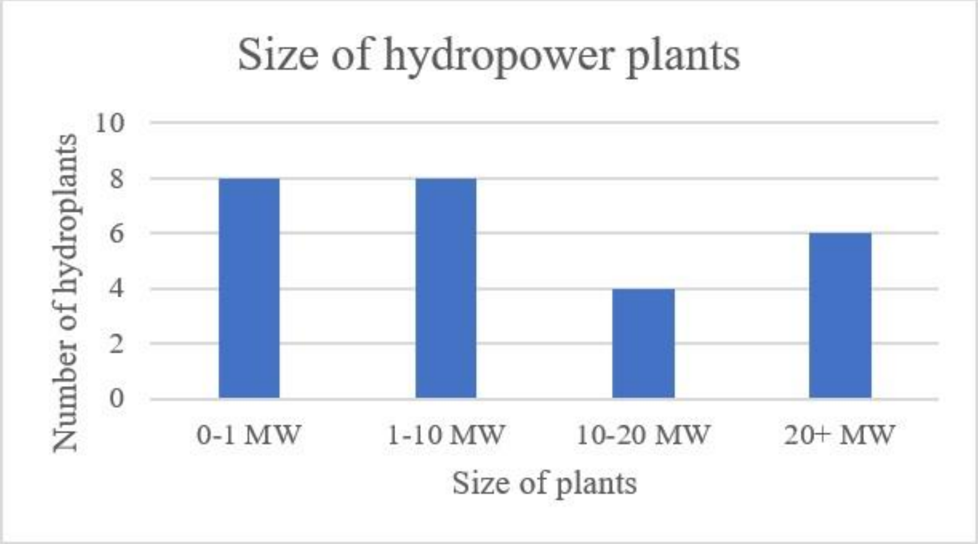


Figure 10. Size distribution of hydropower plants identified in the studied area.

An advantage of hydropower is that it is a dispatchable energy resource, and it is usually easy to regulate the output performance with no significant fluctuation in voltage and frequency [48]. The easy regulation of the of the electricity generation makes hydropower suitable as a renewable option for islanded electricity grids. Various different types of hydropower plants exist, and their sizes range from powering a single residential user to powering an entire city or energy-intensive industry. There are several types of hydropower plants: storage hydropower plants, run-of-river hydropower plants, and pumped-storage hydropower plants. Dammed hydropower plants use storage lakes, and usually require the use of a dam for the creation of an artificial storage lake [53]. This kind of hydropower plant is used for larger outputs. Run-of-river hydro plants take the energy from the natural flow of rivers, though sometimes, short-term storage for a couple of hours up to a day might be available to even the natural river flow [53]. Run-of-river hydropower plants can be found among smaller communities, such as Hoonah, Alaska. The negative environmental impact of these two options differs considerably. Run-of-river hydroelectric plants bypass the original flow of the river, and have a minor impact on fish migration and the landscape as, in most cases, a dam poses an unbreachable obstacle for fish [53], potentially leading to a decreased fish population in the river upstream from hydroelectric plant dams. Furthermore, storage lakes can require vast areas of land, which must be cleared for creation of the storage lake. Run-of-river hydropower plants use much smaller areas of land and, in most cases, only use land needed for the facility’s electricity generation and related channels. Moreover, infrastructure needed for the construction and operation of such plants also result in negative environmental impacts [48].

2.3.3.3. Photo voltaic

The Arctic has long winters with little daylight and, due to the high latitude, direct insolation is even relatively low during the long summer days. Therefore, PV electricity generation may not seem to be a feasible option in the region. However, data collected for this review show that solar power is indeed being used in the Arctic, although it comprises less than 1% of the total electricity generated. In direct opposition to winter daylight, summer daylight in the Arctic makes PV an interesting energy source for some remote applications, such as communication infrastructure, farming, and summer or hunting houses [26]. PV panels can be seen on rooftops in some Arctic villages, but it is difficult to collect exact data on the installed capacity of PV panels, since they are privately installed and privately used systems; they are not connected to a grid and therefore not included in official statistics. Even commercial PV systems have a relatively small size, with approximately 30% of the identified PV plants having an installed capacity of less than 10 kW, which is typical for individual residential use. Many of the remaining 70% of identified PV plants have an installed capacity of 10-30 kW, with only a very few having an installed capacity above 100 kW. In several Greenlandic villages, residential PV systems are attached to houses to lower electricity bills, a result of the efforts of private companies focused on providing sales, support, and construction of small-scale residential PV systems [26]. Electricity generation with solar power in the Arctic shows a high seasonal variation (see Fig. 11).

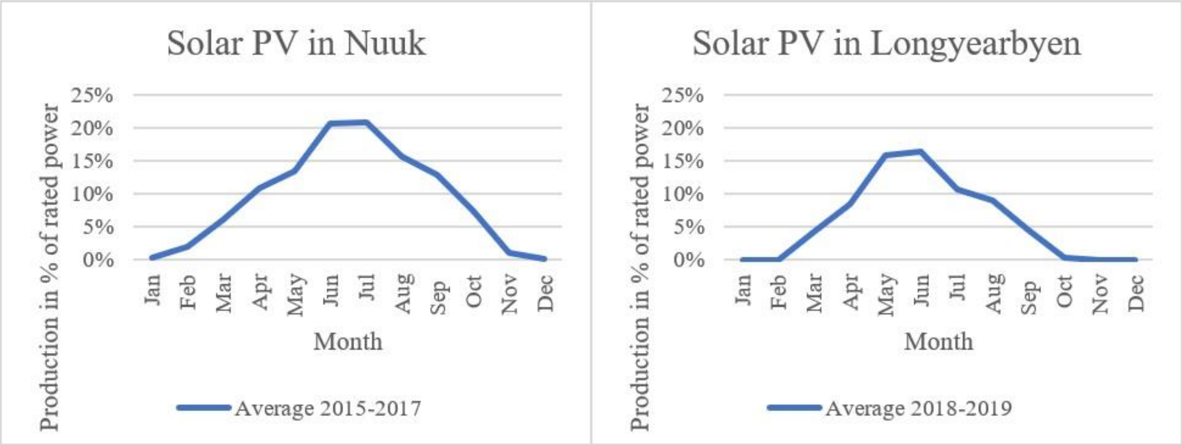


Figure 11. The figures show examples of the use of solar power based on monthly averages in selected locations in the Arctic. Solar power for electricity generation in Nuuk (64°11’01”N, 51°43’ 09”W) (Data provided by Nukissiorfiit the national electricity company of Greenland) and Longyearbyen (78°14’51”N, 15°29’49”E) (Data provided by Avinor the national own airport operator in Norway).

Over the winter, electricity production reaches a low plateau and nearly stops altogether. Another shorter plateau can be seen in summer in June and July. The cold Arctic climate is an advantage to the solar cells as the coldness increases the efficiency of PV panels [54]. Furthermore, during the transition periods between summer and winter, the reflectiveness of snow increases the radiation that can be collected by PV cells [54], which might explain the bumps that can be seen during spring and fall (Fig. 11). In higher latitudes, PV panels are mounted at a much steeper angle than in lower latitudes. A rule of thumb stipulates that latitude can be used as an approximate angle for mounting PV panels, although sometimes such panels are mounted at an even steeper angle so that any snow that lands on them slides off [55]. It is for this reason that, in the Arctic, PV panels are not mounted on rooftops as they are elsewhere, and are often instead mounted on the walls of buildings. According to Christensen [26]; experience from Maniitsoq, Greenland, shows that annual electricity generation of PV panels at this latitude can be approximately the same as that of southern areas. The expected lifetime of PV panels is around 25 years [48], and it takes up to two years to recover the energy needed to manufacture polycrystalline PV cells [48]. Comparatively, the energy demand for manufacturing thin-film PV cells is, essentially, lower. The greatest environmental impact relating to the production of PV panels concerns the toxic and rare materials used in the manufacturing process and the recycling of the panels [48]. Electricity production using PV panels can negatively affect the environment. An example of such a negative effect is land use, assuming PV panels are built on open land. Often, however, PV panels are attached to buildings, making this use of open spaces negligible and thereby reducing their environmental impact.

2.3.3.4. Wind

Wind is a widespread energy source in the Arctic, with a high potential in coastal areas [56,57]. Wind potential is available throughout the year with seasonal variations. Wind energy can be harnessed using wind turbines and analysis (eg. Refs. [32,33]) has shown that a number of installed wind turbines can be found in the Arctic. An advantage of wind energy is that such projects are scalable to desired output, with even small outputs being obtainable. Furthermore, a particularly interesting observation shows that the performance of wind turbines increases under very cold climactic conditions. The US Department of Energy (DOE) observed a 20% increase in maximum power output at around -37 °C, compared to temperate areas [32]. This increased output is related to air density in colder environments, which allow the blades of wind turbines to absorb greater force from the wind. Due to the occurrence of strong winds in Arctic areas the aerodynamic profile of the blades often needs to be modified, or a variable blade angle mechanism used, so that wind turbines can continue operating under strong wind conditions [58]. While this results in reduced performance, the alternative would be the shutdown of the wind turbine.

Obstacles facing the realization of wind power projects are related to the impact of Arctic weather conditions on relevant technology. Some research on technological adaption to the cold conditions of the Arctic has already been undertaken [32,59]. Cold climates can influence material properties, especially at temperatures below -40 °C, examples of which include the deformation of composite material due to different thermal expansion properties, and the increased brittleness of certain metals [37,58,60]. These can lead to decreased structural integrity among wind turbines. Another problem relating to the use of wind turbines in cold climates is icing; icing can change the shape and, therefore, the aerodynamics of wind turbine blades, thereby lowering their efficiency. Furthermore, ice can block ventilation openings, which can lead to overheating, while ice can break off the blades and cause damage. Two different kinds of ice form on the blades of wind turbines: glaze ice and rime ice. Glaze ice is a very hard and transparent ice, it is the result of aqueous liquid dropping on freezing surfaces [58,61]. Rime ice is white and opaque and is not as hard as glaze ice due to the bubbles trapped within it [62]. Rime ice is created when a super-cooled cloud or fog hits a surface below the freezing point [58]. Two different approaches can be found for solving icing problems on these blades, namely, active or passive icing interventions. Examples of passive ice reduction on wind turbine blades is to apply a coating, which lowers the adhesion of ice on the blade [58,63], and the application of black paint to the blades so that they absorb more solar radiation, thereby creating a natural heating effect [44,58]. Comparatively, active icing intervention approaches are inspired by aviation, whereby different technical solutions are used to heat the blades [64]. One example utilizes a fraction of the electricity produced by a single turbine, at around 6-12% of the turbine’s output [58].

Cost approximations show that potential wind energy projects in the Arctic would be two to three times more expensive than those in temperate regions. The price per kW installed capacity is between 2500 and 7000 USD [33]. It must be considered for wind power projects, which relates to the complexity of building solid foundations for wind turbines on permafrost, this often leads to high construction and maintenance costs [65,66]. The generation cost of electricity is reduced to operation and maintenance after the payback period of approximately 10 years [48]. The feasible lifetime of a wind turbine is 20 years, though it can be even longer if the operation and maintenance costs are of an acceptable level [67]. Due to construction and maintenance reason smaller wind turbines are preferred in the Arctic. This is contrary to the global development of increasing the size of wind turbines.

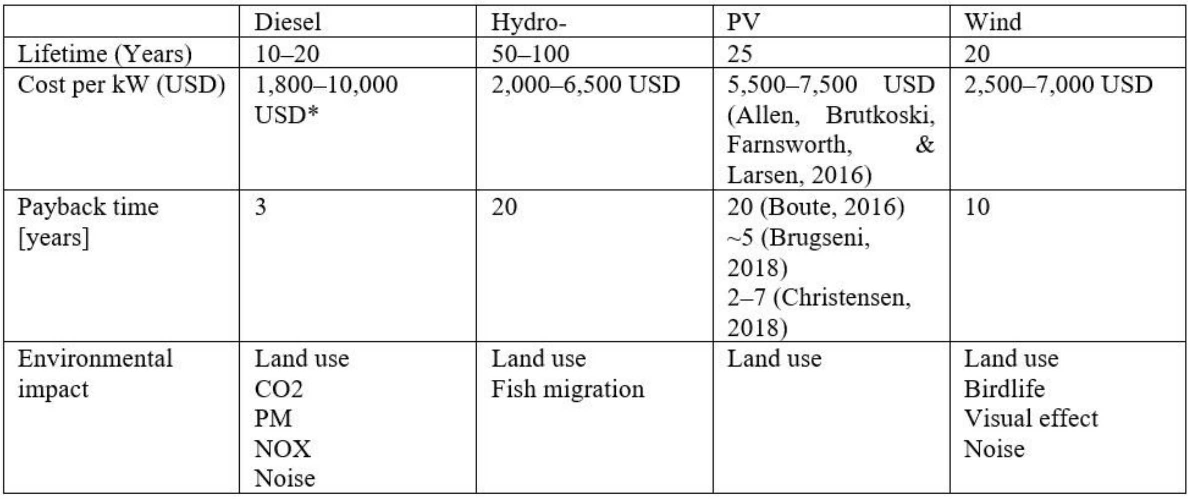
The environmental impact of wind turbines after their installation is relatively low. Wildlife can be compromised due to the possibility of birds colliding with blades [67]. A further environmental impact results from the production of wind turbines and the raw materials used to make them. It takes up to nine month of electricity generation to recover the greenhouse gas emissions emitted during this manufacturing process [67]. The construction of the wind turbines also impacts the local environment in two ways: first, clearance of the worksite has a resulting influence on wildlife and land use [48]; second, the visual effects of the wind turbine, which can lead to flickering shadows and noise creation [68]. This would impact the possibility of erecting small-scale wind turbines for domestic use. Moreover, since communities are generally located at naturally sheltered spots this would lower the yield of wind and the potential harvest of a wind turbine.

2.3.3.5. Summary of the main properties of energy resources

Finding an optimal mix of primary energy resources is critical to achieving energy security. The selection of the energy sources should be done in accordance with a good energy policy which takes into account the three criteria; environmental soundness, security of energy supply and affordability [69].

A summary of the main electricity generation methods used in the Arctic and a comparison of their key elements is presented in Table 4. There it is important to consider the vast range of diesel engine sizes which are in use across the Arctic. This results in a high spread of cost per installed kW for diesel engines.

Table 4. Summary of the main properties of energy generation technologies and energy sources in the Arctic. * The high spread in cost per kW is the result of the vast range of engine sizes.



	Diesel	Hydro-	PV	Wind
Lifetime (Years)	10–20	50–100	25	20
Cost per kW (USD)	1,800–10,000 USD*	2,000–6,500 USD	5,500–7,500 USD (Allen, Brutkoski, Farnsworth, & Larsen, 2016)	2,500–7,000 USD
Payback time [years]	3	20	20 (Boute, 2016) ~5 (Brugseni, 2018) 2–7 (Christensen, 2018)	10
Environmental impact	Land use CO2 PM NOX Noise	Land use Fish migration	Land use	Land use Birdlife Visual effect Noise

In the previous sections we have described the most widely used energy sources and technologies in the Arctic. In the following we give a brief introduction to more novel technologies and energy sources in the Arctic. Among the less used energy sources is geothermal energy, which is available in some Arctic regions, mainly along the ring of fire in the Aleutian Islands [56]. Geothermal energy has proven to be suitable for cold regions in Iceland [48]. Biomass energy is another example of a novel energy source which converts living plant matter or organic waste into energy [48]. In the Arctic living plant matter is scarce but creating energy from organic waste could be of interest. Yet, the technology is not established in Arctic conditions [71]. Tidal and Current energy can be a solution for coastal communities in the Arctic. However, the impact of sea ice, drift ice and icebergs have not been studied sufficiently, and further research and development would be needed to adopt that technology.

2.3.3.6. Back-up sources

A secondary energy source is often needed for the supply of energy should the primary electricity generation source break down. In most cases, diesel generators are chosen as secondary energy sources because the efficacy of this method has been proven in recent decades, and because they have a short cold start time [31]. It is important for secondary energy sources to be both reliable and predictable and it is for this reason that, in theory, any dispatchable energy source can be used as a back-up source.

The data collected on the studied area show, that in small communities, electricity production is split among several generators [15]. Only in a few cases are two generators of the same capacity used in this way; one for production, the other as a back-up. Generally, three or more generators are used. If one generator breaks down, the loss can be covered with a back-up generator, as explained further in Section 3.4.1, while cold starting these generators only takes a few seconds to a few minutes [17], thereby reducing back-up capacity needs. According to the study data collected in Greenland and Canada, back-up capacity within individual communities is around 50% (42-59%) of the installed capacity for normal production. The combined systems security is even higher as, in most cases, it can be assumed that normal production capacity is over dimensioned. However, when necessary, back-up capacity can also be used to cover peak demands that might occur during wintertime when additional electricity is needed for heating and lighting, as shown by the study data. Even in cities powered entirely by hydropower plants, diesel generators are often installed as a back-up source of electricity, or to cover peak loads, as can be seen in the case of Nuuk, Greenland. Another option for secondary energy sources is that of an energy storage solution such as battery storage or pumped hydro storage for securing a short-term electricity supply. Together with the introduction of several renewables, diversification of resources will increase the reliability of the overall system. Such a system has the capability of being self-sustaining without using fossil fuels.

2.3.4. Energy security as a socio-economic factor of energy use

The following section is structured according to the International Energy Agency's (IEA) definition of energy security as "uninterrupted availability of energy sources at an affordable price" [72]. Both of these attributes of energy security-uninterrupted availability and affordability - are elaborated in the following section. Uninterrupted availability of electricity, and affordability, is important for human wellbeing. Affordability is an especially important issue in regions impacted by high rates of unemployment, poverty and low income households and an already high cost of living [49].

2.3.4.1. Availability

Cold climate conditions in the Arctic make secure supply of electricity particularly important [39]. On investigation, the value of lost load (VoLL) in temperate areas reveals a huge difference between industry (280 USD/kWh) and private use (50 USD/kWh) [73]. VoLL calculates the loss to an economy due to non-delivered electricity. It can be expected that, for Arctic areas, there is a significant social component to VoLL, which changes over time. During long interruptions, infrastructures can suffer from significant damage, due to such eventualities as frozen water pipelines.

It is important to have redundancy in the grid if such long-term interruptions are to be avoided. However, the relatively small-scale isolated grids in the Arctic are disadvantaged in terms of reliability because they have less redundancy in the grid infrastructure. Grids are often designed as parallel-distribution systems [74], which allows these systems some redundancy, and helps to reroute electricity flow in case of partial failure. Systems redundancy can be stated as N + X, where N represents the primary supply and X represents the degree of back-up [75]. For example, three generators of the same type can be installed, even though just two are needed for operation; accordingly, one generator is used for backup (see Fig. 12). Such a set-up would represent a system with N+1 redundancy, which means that, if one generator breaks down, the system can operate normally without compromise.

Currently, electricity grids are islanded in most remote Arctic communities, and have no connections with regional electricity grids. Among such communities, electricity infrastructure is organized in a centralized manner, with electricity generation taking place in several locations in the village. Adding renewable energy sources to these infrastructures can change their electricity generation patterns. Accordingly, electricity generation would take place in a more decentralized manner, leading to the creation of so-called micro-grids (MG). A MG is a clearly defined distribution system with multiple decentralized interconnected energy sources and loads that act as a single controllable unit [18,76].

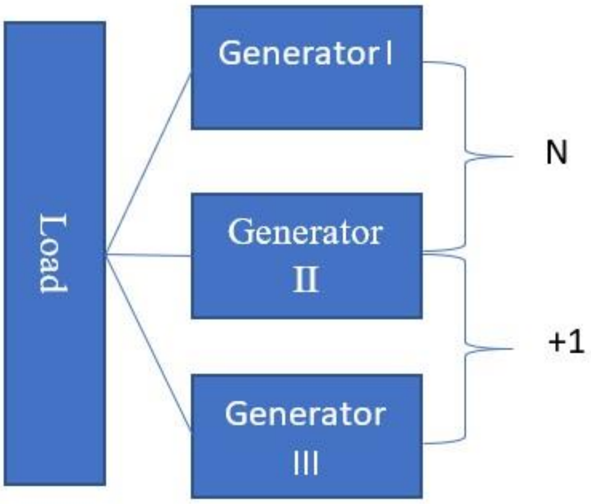


Figure 12. N+1 redundancy: under normal circumstances generator I and II operate in parallel; if generator I fails, generator III can jump in and replace it. Subsequently, generators II and III take over the operation.

Unpredictable energy sources such as PV and wind energy can cause fluctuations in voltage and frequency in the electricity distribution system. To avoid such fluctuations, an intermittent energy storage is needed as elaborated in section 2.3.2. To ensure a secure energy supply for the specific combination of distributed energy sources and energy consumers, primary and secondary the microgrid infrastructure has to be tailored. The supply variation as well as the variation in demand must be included to find the right dimensions for the different energy generation options and the right energy storage technology and size. Every case has to be planned individually, and there is no one fits all solution for each case. Several special impacts on transmission grids can be found in the Arctic, and these relate to the harsh weather conditions. Storms and icing can severely impact transmission grids and cause infrastructural collapse [59,74,77,78], while further risks can be created by animals or accidents. Risks of trees damaging electricity lines appears in an Arctic context more in sub-Arctic areas, where it is more likely outside the settlement boundaries [74]. Trees, especially in temperate areas, are a main external reason for interruptions to electricity supply, which can be temporary or permanent [74].

2.3.4.2. Affordability of electricity in the Arctic

A critical factor analyzed in this review is the affordability of electricity among unconnected Arctic communities e and with reference to the IEA's definitions of energy security. To analyze electricity affordability, data were collected on electricity prices and the income distribution within these communities. Electricity prices were identified for 313 Arctic and Sub-Arctic communities (see Fig. 13). Electricity prices in over 100 communities ranged from 15 to 30 USD ¢/kWh. Results show that all Greenlandic communities fall within this range, with an average price of 26 USD ¢/kWh. That is the result of the policy of 'equal unit price' on electricity and water which was introduced in Greenland on the January 1, 2018 [45]. Furthermore, Fig. 13 shows that many areas have an electricity price in the range of 60e75 USD ¢/kWh. In all the other studied areas we can find smaller clusters with a common price, which is the result of the existence of regional grids or because the settlements concerned have the same provider. The lowest and highest price found among the data relate to the same region, Alaska, 8 USD ¢/kWh in Nuiqsut and 181 USD ¢/kWh in Healy Lake. For comparson, in Europe the average cost of electricity in 2018 was 25 USD ¢/kWh, though this price ranges from 12 USD ¢/kWh in Bulgaria to 37 USD ¢/kWh in Denmark [79].

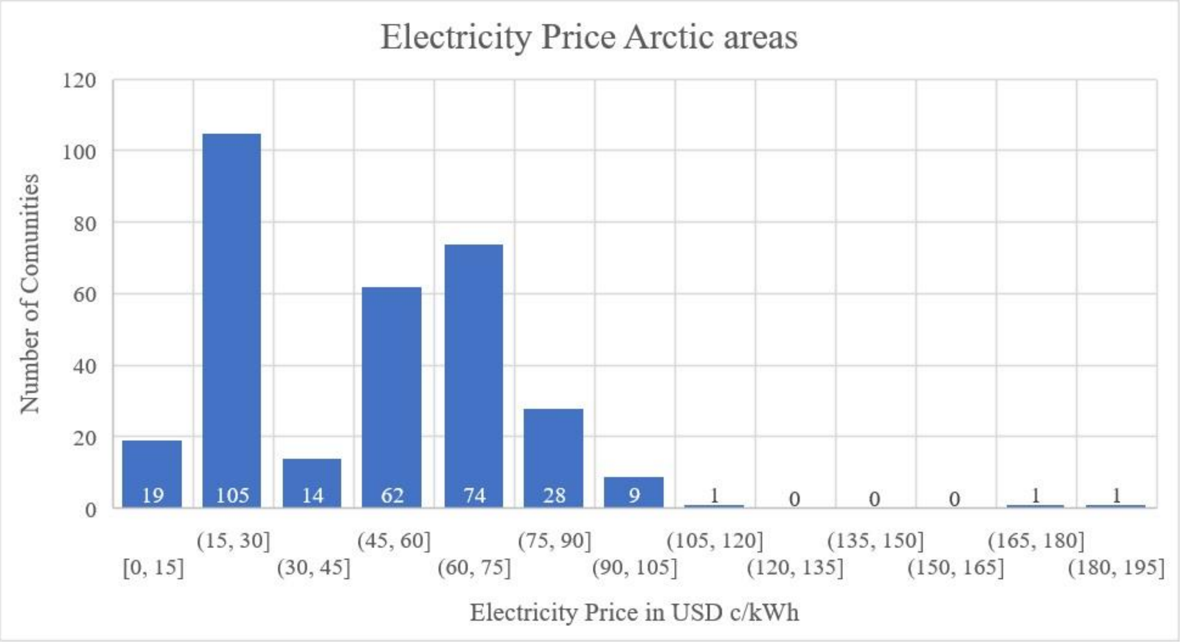


Figure 13. Electricity price in Arctic areas, which can range from 8 to 181 USD ¢/kWh (both prices are found in Alaska).

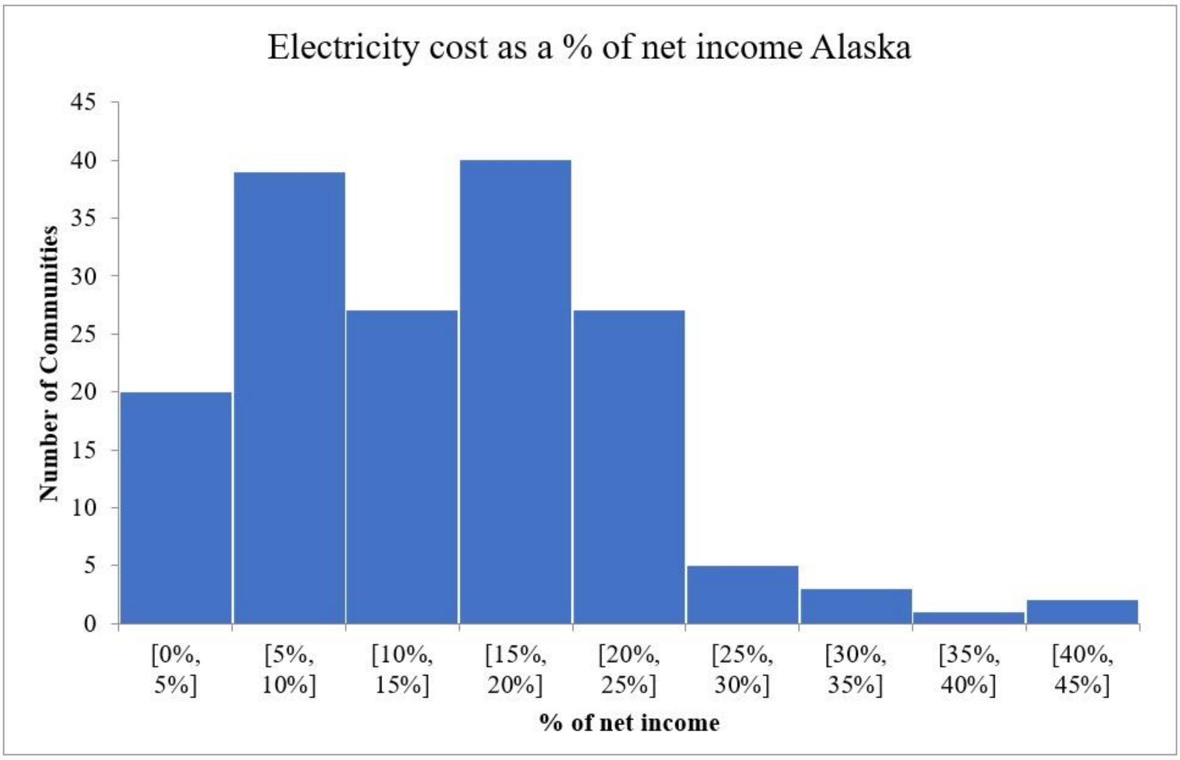


Figure 14. Electricity cost as percentage of the net income for rural Alaska.

The cost of electricity can comprise up to 47% of a household's net income (see Fig. 14). A closer look at those communities in which households spend more than 27% of their net income on electricity reveals that their net per-capita income is below 8500 USD, and that their electricity prices are 79-90 USD ¢/kWh. About 55% of those communities that have installed renewable energy sources for electricity generation spend below 10% of their net income on electricity; the remaining 45% spend 10-31% of their net income on electricity. The US average spends 2-3% of the income on electricity [81]. It can be expected that in those areas with high electricity prices, there is a greater tendency to invest in energy efficiency and employ a more careful use of electricity. This would result in lower electricity consumption in high cost areas. The representation in Fig. 14 is based on the average electricity usage in Alaska, and therefore may be an overestimation of money spent on electricity in relation to the net income of households.

Data availability for rural Canada was insufficient, yet the percentage of net income for electricity cost can be expected to be slightly lower. For rural Canada electricity prices peak at 100 USD ¢/kWh as compared with 181 USD ¢/kWh seen for Alaska. Both regions have problems associated with low income and high poverty rates [49,50], which makes high energy costs a critical challenge in achieving energy security.

In Norway, Longyearbyen, for example, 3.5% of the net income is spend on electricity. Average electricity consumption data were unavailable for settlements in Greenland, and so these data were assumed to be the same as those for Alaska due to a similar way of life with a high portion of subsistence and environmental conditions, of long and cold winter-times. It is also interesting to note that the electricity is a greater burden in rural areas (see Fig. 15) for settlements in Greenland, though electricity prices in Greenland are unified, and the percentage related to the net income is merely due to differences in income between towns and settlements.

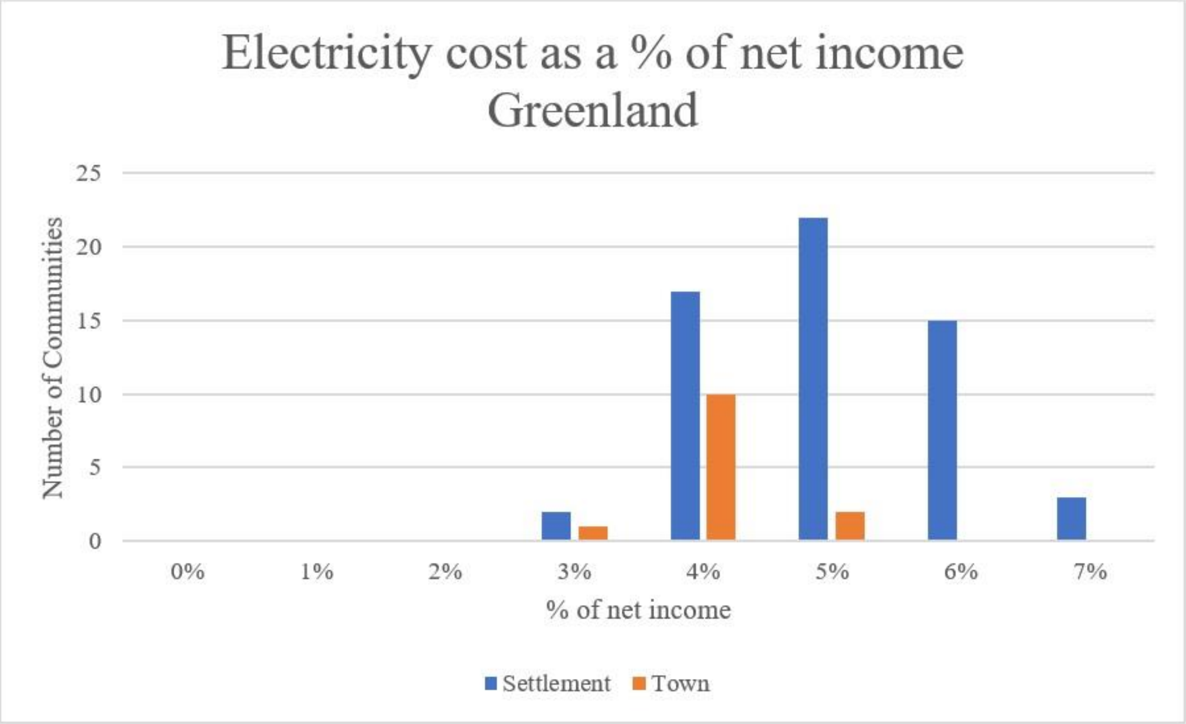


Figure 15. Electricity cost as percentage of the net income for Greenland. The data set is divided into settlement (blue) and towns (orange).

2.4. Conclusions and future work

Research shows that several renewable energy sources are currently in use across the Arctic, with the percentage of renewable energy sources being slightly higher in the studied area than the global average (see Section 2.3.1). For successful integration of renewables, further development will contribute to realizing more cost-competitive technology. This will lower the high upfront cost of investments in renewables, which can be a restriction, especially for smaller communities. For larger communities, the upfront cost will remain high, although the cost per kW of installed capacity can be expected to decrease with the creation of larger hydropower plants.

Diesel is by far the most dominant energy source among Arctic communities, although the use of diesel generators brings about several negative consequences, including the risk and cost involved in transporting diesel, the high cost burden for local communities, and diesel's environmental impacts, and thereby also challenging the ability to achieve energy security. All the afore mentioned factors result in high electricity cost for the end consumer. Renewable energy sources show their capability of reducing such impacts. Currently, hydropower is the most used power source of all renewable energy sources in the Arctic. Where hydropower resources are available, they can provide affordable electricity. Wind and PV power also offer huge potential in the Arctic because they are suitable for various sizes of communities and do not need specific natural conditions such as those needed by hydropower plants.

Energy security is critical for Arctic inhabitants, with affordability and availability being central elements to the well-being of local communities. Further investigation is needed to support the transition towards a more sustainable energy future in the Arctic. One part of this investigation relates to technological development for the use of renewables and how technology from lower latitudes can be adopted for use in the Arctic. Further investigation on how a transition can be stimulated from an investment perspective and operation costs, including a more detailed cost benefit analysis is also needed. The transition to more sustainable energy systems is both very important and very challenging for Arctic communities. Politicians and other decision makers therefore need rigorous evidence-based support to come up with strategies for a successful transition towards a more sustainable future.

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3. Paper 2

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

3.1. 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.

3.2. 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.

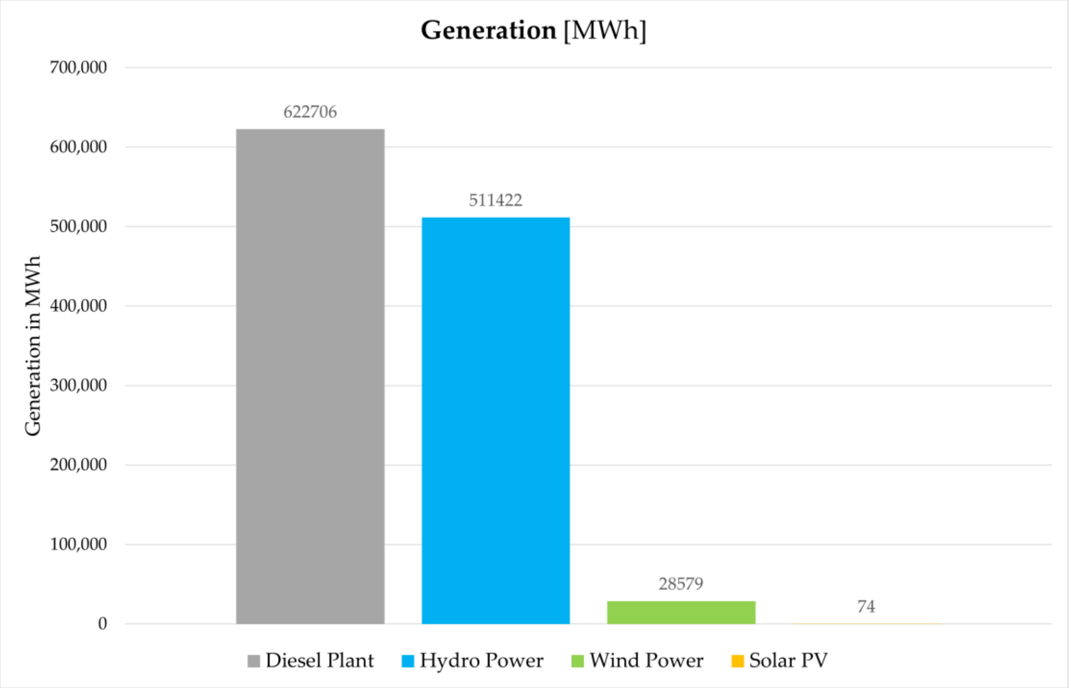

Figure 1. The figure shows the share of electricity generation (in MWh) among diesel generators, wind generators, and generation using hybrid systems. Hybrid systems combine diesel generators with non-dispatchable energy resources, such as wind and photovoltaic (PV) power.

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.

3.2.1. 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 hours 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.

3.2.2. Energy Storage

Energy storage is crucial for the successful transition to renewables in islanded energy systems (see Section 3.2.3). 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].

3.2.3. 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 3.2.1), energy storage (see Section 3.2.2), 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 fulltime, 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].

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

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 3.4 provides a brief general discussion of the potential for renewable energy resource use in the Arctic, followed by conclusions in Section 3.5.

3.3. Research Methodology

3.3.1. 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.

3.3.2. 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 Interviews and Databank Harvesting) 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 3.4.1. 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 2,000 to 3,000 inhabitants.

- Transportation infrastructure is limited; communities are primarily connected via planes or boats, which means that port and airport infrastructure is available. 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.

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.

3.3.3. Literature Review and Data Collection

3.3.3.1. 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 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.

3.3.3.2. 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.

3.3.4. 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 3.2.3). 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 3.2.1 and 3.2.2) and renewable energy penetration level (see Section 3.2.3). The set of secondary variables required is explained in greater detail below and is presented in Table 1. 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.

Table 1. Overview of the assumptions for the scenario analysis.
* variable depending on the community.

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&M Diesel	0.02	$/kWh	[42]
O&M Solar	9	$/kW	[43]
O&M Wind	3	%	[44]
O&M Hydro	2	%	[45]
Install. cost solar	2,500	$/kW	[27]
Install. cost wind	2,500	$/kW	[46]
Install. cost hydro	7,000	$/kW	[22]
Capacity factor PV	15	%	[27]
Capacity factor Wind	33	%	[47]
Capacity factor Hydro	50	%	[48]

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[1] can lead to significantly higher CO2 price recommendations. Setting the price of CO2 to the lower end is more favorable for the

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[1] https://www.climateinteractive.org/tools/en-roads/, accessed on 25 July 2019),

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. Overview of the penetration levels used in the case studies in Section 3.3.1.
* in Kotzebue, the value of 25% was taken to represent the actual situation.

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%

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.

3.4. Results and Discussion

3.4.1. 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	2,144	2,534	3,153
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%

3.4.1.1. 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.

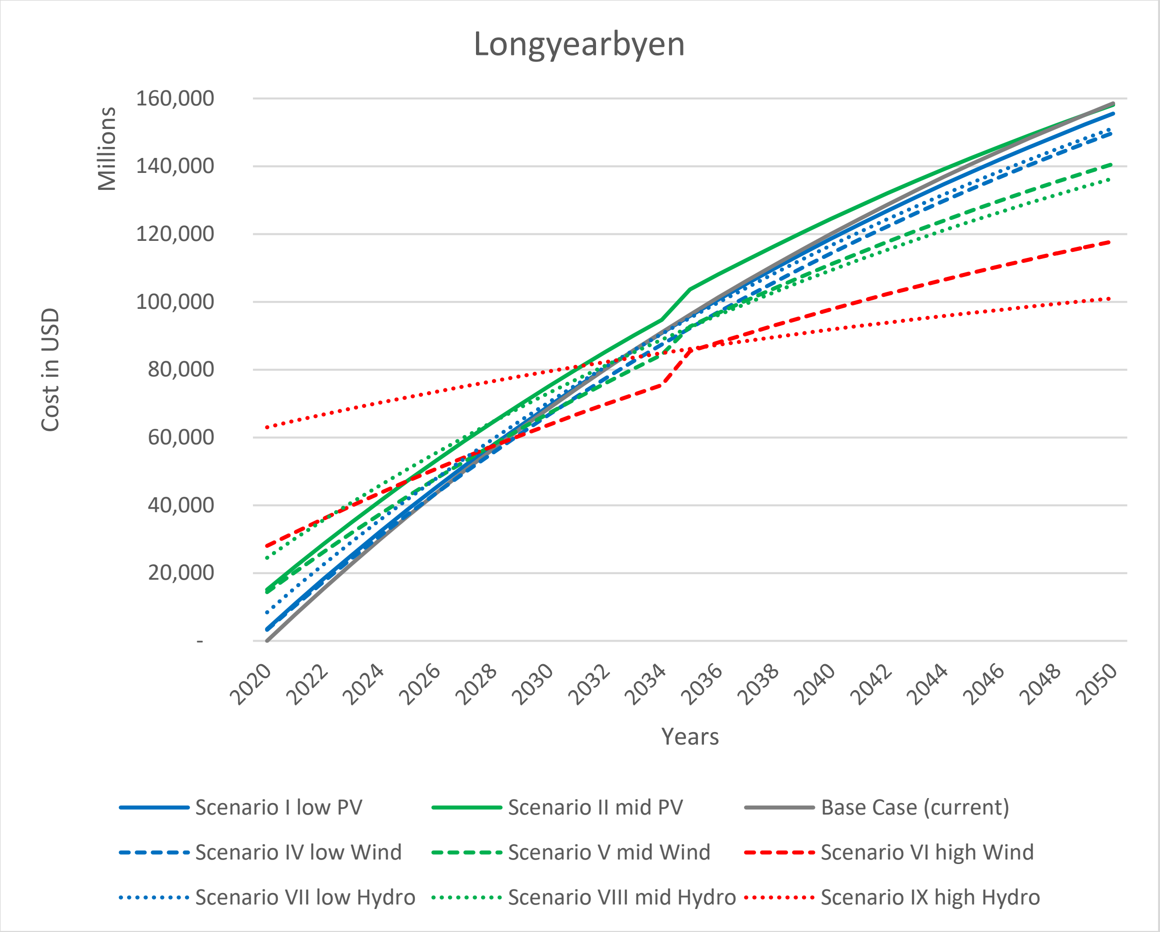

Figure 3. Scenario analysis of possible power generation for Longyearbyen shows the accumulated net present value of cost for power generation with a coal price of 0.1 $/kg; capacity factor of 40%; and fuel consumption of 1.75 kg/kWh. The other input data are explained in Table 1, and the scenarios are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

3.4.1.2. 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.

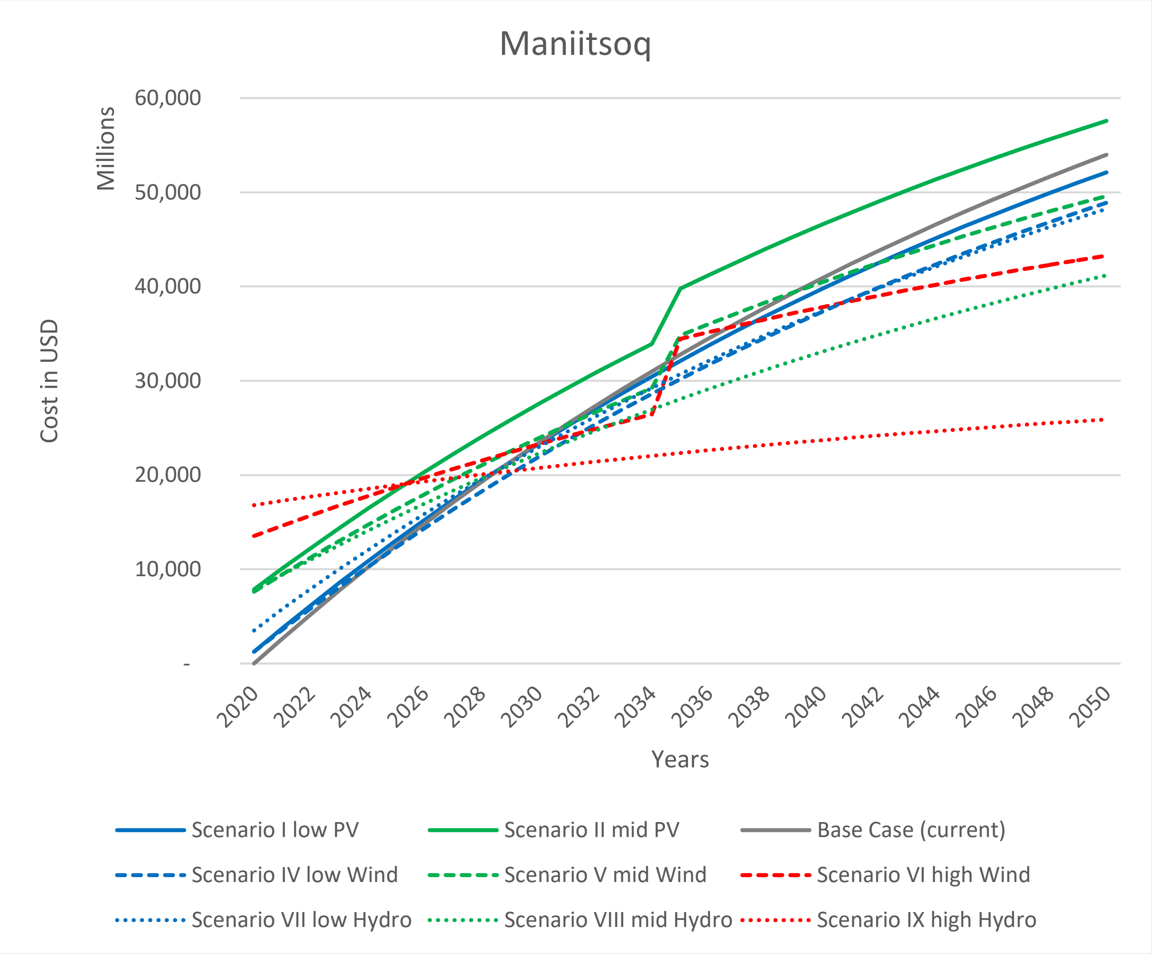

Figure 4. Scenario analysis of possible power generation for Maniitsoq shows the accumulated net present value of cost for power generation with a diesel price of 0.85 $/l; capacity factor of 28%; and fuel consumption of 0.25 l/kWh. The other input data are explained in Table 1, and the scenarios are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

3.4.1.3. Kotzebue

Kotzebue is a coastal and predominantly indigenous community situated in Alaska above the Arctic Circle (66° 54′ N, 162° 35′ 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.

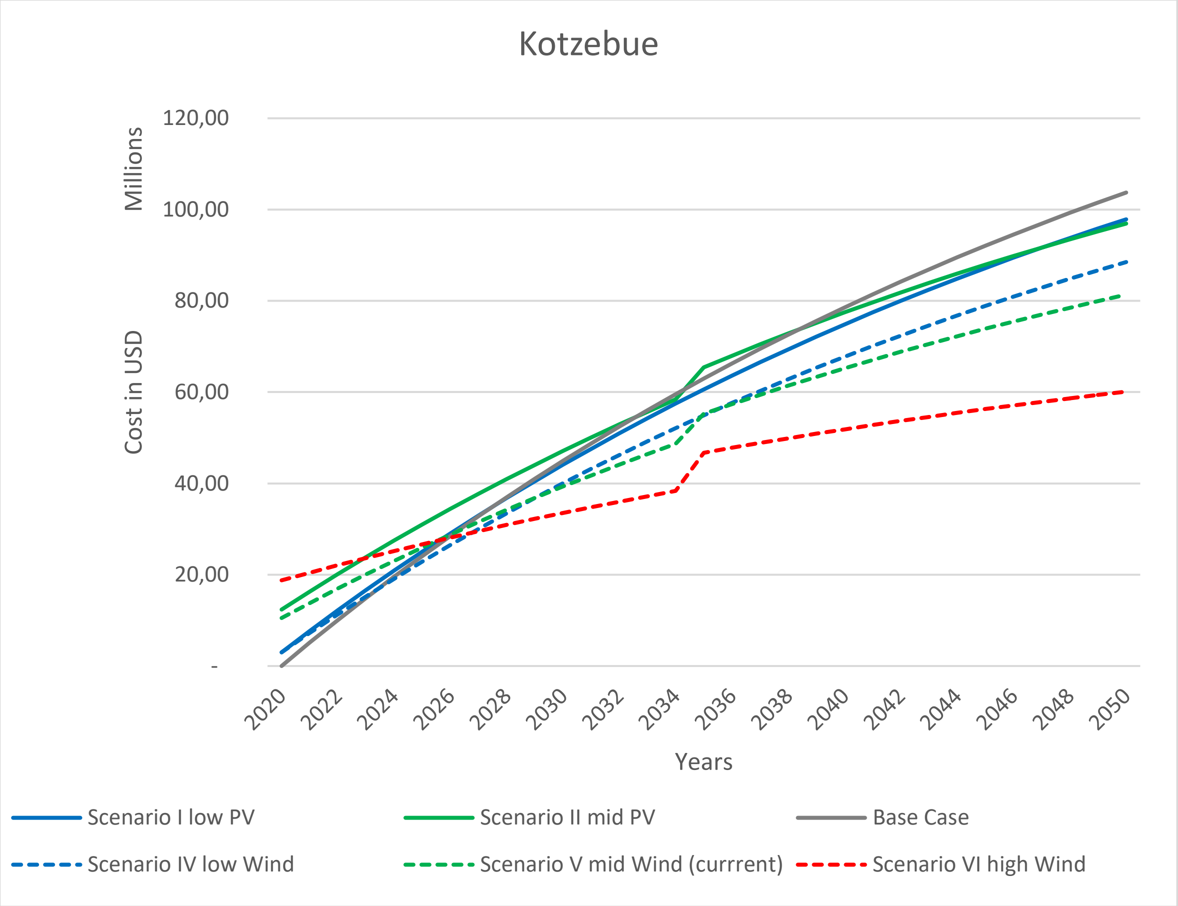

Figure 5. Scenario analysis of possible power generation for Kotzebue shows the accumulated net present value of the cost for power generation with a diesel price of 0.91 $/l; capacity factor of 17%; and fuel consumption of 0.28 l/kWh. The other input data are explained in Table 1, and the scenarios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

3.4.2. Social Impacts

3.4.2.1. 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 communities 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.

3.4.2.2. 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].

3.4.2.3. 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.

3.5. 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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4. Paper 3

Simulation of Pathways Toward Low-Carbon Electricity Generation in the Arctic

4.1. Introduction

The energy systems used to power remote Arctic communities are unique. In the Arctic, as elsewhere, electricity is the backbone of modern society. Arctic communities are typically located several tens to hundreds of kilometers from one another and are home to relatively small populations striving to create a good life for themselves in an often harsh and challenging environment. The conditions in the Arctic complicate the installation of various infrastructural supports, such as overland lines, due to hazards associated with construction on permafrost. Overland lines are typically constructed adjacent to roads or railroads, which are rare in the Arctic. The costs associated with the establishment of a cross-regional electricity grid to serve remote Arctic communities are prohibitive, and, in light of the small market that could be entered, such an undertaking holds little appeal or benefit for energy providers and grid operators. Due to an unlikely grid extension toward remote Arctic communities, these communities need to be energy self-sufficient.

In recent decades, Arctic communities have managed to operate independent energy grids. In approximately 80% of these communities, the grids are powered solely using diesel generators [1]. The negative environmental impact associated with burning diesel and the resulting greenhouse gas and particulate matter emissions is well known. However, the transportation of diesel to the point of use for electricity generation is often complex and costly. Permanent transportation infrastructure is limited in the Arctic, with few permanent roads available to facilitate fuel delivery. As such, fuel must be transported over temporary pathways. Transportation methods include trucks on ice-roads during wintertime, barges on navigable rivers or the sea during summer, and occasionally, when neither of the latter two modes is possible, the use of air transport. All three transportation methods require complex planning and are contingent on conducive weather conditions. The region’s extreme conditions make fuel transportation risky, and result in high transportation costs. These high transportation costs in turn result in high electricity prices, perhaps as high as 1.80 $ per kWh [1], as fuel must be burned to generate electricity. Moreover, unemployment and poverty are common challenges in Arctic communities [2] [3], and the high electricity prices impose significant additional cost burdens on inhabitants [4].

Renewable energy sources have demonstrated significant potential to reduce energy costs [5], and the feasibility of their use for electricity generation under Arctic conditions has been demonstrated [5] [6] [7]. However, the energy transition process is likely to be exceptionally challenging because of the harsh climate and remoteness in addition to financing difficulties. The technical equipment typically used for energy generation must be adapted to the harsh climatic conditions [8]. While some technical solutions already exist, the construction process itself and the requisite logistics for the construction are challenging and cost intense [9]. Accessibility to many remote communities is challenging; in some cases, only two barges run per year, one after the ice has melted and the other before the sea freezes [10]. Owing to the need for special equipment and complex construction, the costs of integrating renewable energy sources in the Arctic is higher than in temperate areas [9]. Considering the different costs associated with the installation and subsequent operation of renewable energy technology in the Arctic, a meticulous investigation of the transition process is essential. Several cases have indicated that energy transitions may be financially viable under Arctic conditions—in Kotzebue, Kodiak, and Nuuk, for example [10] [11], where renewables have been installed and operated for some time and their financial feasibility has been demonstrated.

This study sheds light on the transition process by analyzing the different scenarios within which renewable energy sources may be integrated for the purpose of electricity generation, focusing on potential financing solutions to mitigate the investment risk associated with uncertainties and climatic challenges [7]. The investment costs associated with installing the facilities required to generate electricity using renewable energy sources are high and thus may hinder the transition toward the use of renewable energy sources. The scenarios differ with respect to the various financing tools available to support the energy transition. Such financing might involve subsidization with a CO_2 tax, consistent dedicated support for renewable energy sources, or no support at all. Revenue from a CO_2 tax could be introduced to subsidize the integration of renewables. Constant support would come from a source exogenous to the energy system analyzed in this work. The scenarios analyzed herein comprise various cases representing different energy transition integration speeds and starting times. The speed and start of the energy transition in the model depend on public pressure and policymaker's decisions. The analyzed cases are compared with a "business-as-usual" case to see if the use of renewables is beneficial. Also, the study investigates how different integration patterns affect electricity costs.

In the context of remote Arctic communities, this study addresses the overarching question of which financial tools can best support the introduction of renewables into remote Arctic microgrids with a focus on three key aspects: technical, social, and financial. A set of underlying research questions must be addressed in responding to the overarching question: for example, how can different integration pathways support the energy transition? The energy transition pathways can be described by different integration speeds, subsidy models, and degrees of social acceptance, which are answered in the following paper. Regarding the technical aspects of the energy transition, the following questions, which have been elaborated on in preliminary studies [1] [12], are crucial to execute this study. Which technology options are available for the transition process, and can they be used or adapted to the specific location [1]? Article [1] concludes that hydropower is well proven with a high potential of electricity cost savings. Moreover, wind and photovoltaic (PV) have been proven to work under Arctic conditions with a significant cost saving potential. How does the transition toward renewables with an increased share of non-dispatchable energy sources affect energy security [12]? Article [12] concludes that locally generated renewables can help to increase the mid-term energy security by increasing the independence from fossil fuels. On the other hand the short-term energy security can be slightly lowered by using a higher share of non-dispatchable energy sources due to production fluctuations. This demonstrates that the technological requirements for the energy transition in the Arctic has been studied extensively. Energy policy has also been investigated along with how the implementation of renewable energy in Arctic communities might best be supported [12]. However, the ideal approach to financing investment in renewable energy projects to support the transition process remains unclear. In the following sections, the system dynamics method is used to address the financing issues, which is explained in addition to the setup of the system dynamics model.

4.2. Research Methodology

System dynamics (SD) is the method used in this study. SD is a method that analyzes complex processes or problems using a model of the real-world situation. The model, which is an abstract simplification of the real world rather than an exact representation [13], should mimic the behavior of real-world decision-makers [14], and it is essential to identify the optimal ratio between abstraction and detail in the modeling process. SD's particular strength in the context of this study is that it is a powerful tool for analyzing complex systems for which real experiments can be difficult and costly [15]. It is often used in project and change management to analyze the impact of delays and interruptions, which may be expected in the renewable energy integration process. Advance knowledge of and preparation for delays and interruptions can ensure a more stable energy transition process and minimize rework and adjustments [16]. The SD method involves the creation of a structural model of the situation with an integrated feedback function backed up by a "cause-and-effect relationship within the system" [16]. This feedback function can help facilitate a more detailed analysis of the decision-making process [17]. The feedback can represent, for example, non-linear interactions between elements in the system, management decisions, or performance measurements, as are anticipated in the policy aspect of this study [18]. Feedback is crucial for large-scale projects such as the energy transition, for which the performance of more traditional models and methods, such as Gantt, PERT, and critical path, is limited. SD can take feedback effects into account to facilitate problem-solving [19]. More specifically, SD examines the impact of feedback between different elements within a complex system. The feedback need not follow a linear relationship, which is often crucial for the detailed analysis of management and policy actions [18] [17]. Non-linear feedback is expected to be highly significant in the evaluation of different policy strategies for energy transition pathways. The transition of energy systems such as that under consideration in this study will likely encounter various feedback loops and non-linear behaviours throughout the transition process. Another key strength of SD is that the results are easily communicated. A causal loop diagram (CLD) may be used to communicate results to individuals who are not trained in SD because it is a highly intuitive representation of the situation [13]. Therefore, we believe that SD has significant potential for analysis of the transition process in remote Arctic communities. SD has not been used hitherto to analyze transition processes of islanded microgrids. Nevertheless, it has exhibited exceptional potential for other transition processes [20] [21] [22] [23] [24] [25] and has also been employed in more holistic energy transition studies [26].

To obtain a first-hand impression of the situation, 42 semi-structured in-depth interviews were conducted with local government representatives for energy, environment, infrastructure, buildings, and residential consumers. The interviews were conducted in Svalbard, Nuuk, Maniitsoq, Napasoq, Anchorage, Kotzebue and Noatak in the period from November 2018 till August 2019. Semi-structured interviews have a guiding structure based on leading questions [27] [28], but the design also has the flexibility to guide the interviewer toward the collection of information that the interviewer has not planned in the preparation phase, allowing them to probe further into compelling topics that are of particular importance or complex issues [29] [30] [31]. Reflection on the main findings at the end of the interview can prevent misunderstandings [31].

The SD model used herein is based on a literature review pertaining to Arctic energy and the results of field visits and expert interviews. This work's underlying hypothesis is that the current energy system is characterized by a high level of inertia because all existing infrastructure has adapted to the current situation. The system may be said to have reached a path dependency, leading to the hypothesis that a significant initial force is needed to start a change of state in the system. The initial force may assume the form of a government-issued policy, such as regulations, taxes, or fiscal incentives. As soon as an initial force has been introduced to the system, the system is expected to progress gradually from fossil fuels toward renewable options. The integration of renewables is expected to show an oscillating movement on the energy cost side because the system incorporates a corrective mechanism to evaluate the energy price in accordance with the generation costs. The SD model's boundaries and key variables are detailed in the section that follows.

4.3. The System Dynamics Model

An SD model was developed in this research to analyze the energy transition, based on a literature review and interviews. Furthermore, the model may be used to analyze the robustness of energy prices against sudden, unanticipated events. The sub-system model in Figure 1 demonstrates how the model's major elements interact with one another and the main input variables. The sub-system model contains the three sub-systems. Figure 1 shows how the current energy generation sub-system and economy sub-system interact with one another and link to the policy sub-system. The economy sub-system includes the Arctic's energy market and evaluates the change in energy demand, the initial energy demand is based on the literature review and the results from the field visits. The policy element represents the strategies for implementing renewables and allows the user to analyze different financing tools and the resulting strategies for implementing renewables in the Arctic. The energy generation sub-system evaluates the electricity generation cost with respect to political and economic requirements. All parts are further explained in the following.

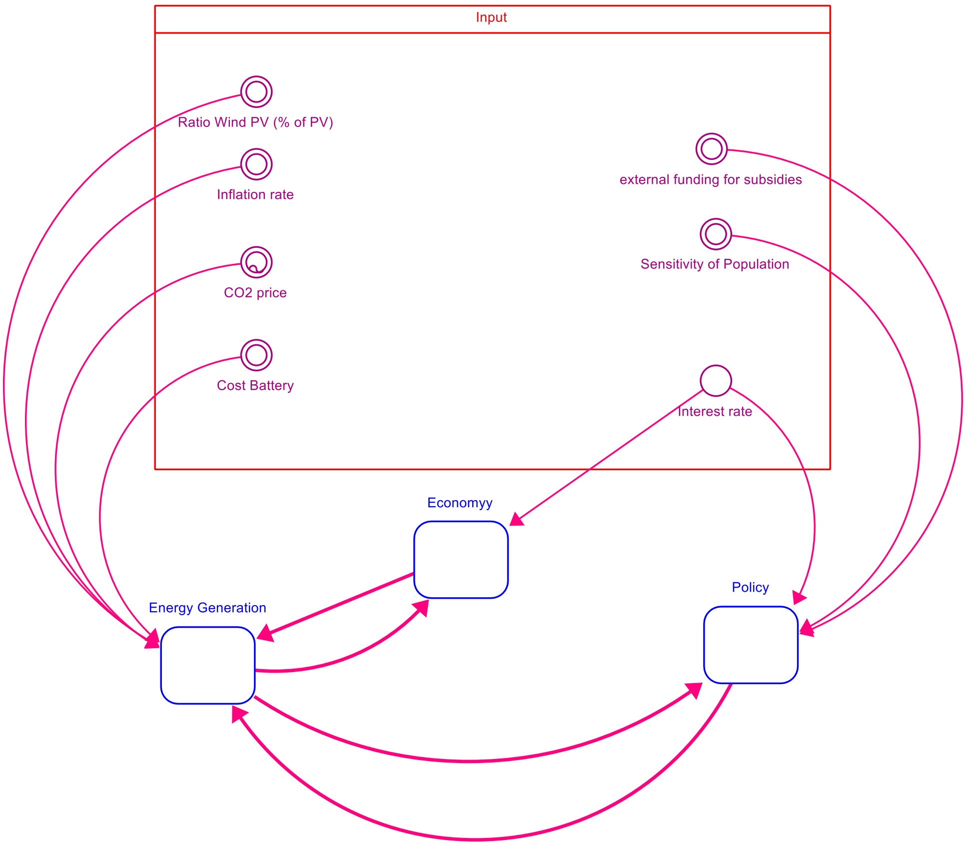

Figure 1. Sub-system Model showing how the three sub-systems—Energy generation, Economy, and Policy—interact with one another. The input box represents variables assumed to be changed by the user to create different scenarios.

4.3.1. System Boundaries

System boundaries are a crucial element in SD. The boundaries define which variables are endogenous or exogenous. A key element related to determining the system's boundaries is the degree of abstraction. It is essential to simplify the real-world problem to such a level that it becomes a manageable system. However, it is also important that the system is not oversimplified, which would lead to results that are not usable.

The model's major limitation concerns the technology options considered. The simulation is limited to three technology options: wind, PV, and diesel. Within that domain, the model assumes a certain degree of technological development. However, should a new energy generation technology arise under Arctic conditions, the model will not have the capacity to accommodate it.

The impact on climate change resulting from the community's greenhouse gas emissions is excluded from the model. Nevertheless, climate change is incorporated into the exogenous variable 'climate change', which provides input regarding public pressure on policymakers. The variable assumes climate change according to the 2°C IPPC scenario [32]. The economy is analyzed on a community level; the policy component considers only local decision-making, while national-level policy is reflected in the variable ‘external funding for subsidies’.

4.3.2. Assumptions and Key Variables

The model represents a fictive Arctic community with a population of 3,150[2] inhabitants. The variable values for similarly sized Arctic communities, such as fuel cost and operational and maintenance cost, were identified during the field study. The literature review identifies other variable values, such as climate change, as Table 1 shows. Changes in the variable over time have been implemented based on predictions from the literature review and shown in Table 1. Regarding renewable energy’s potential, an ideal availability was assumed. More detailed wind and solar data would be necessary for more precise analyses and to account for location-specific variations.

Technology options for renewable electricity generation may be found at various maturity levels for Arctic conditions. The SD model aims to be universally applicable to Arctic communities; nevertheless, the model’s values must be adjusted for each community. Only mature and well-proven technologies are considered; nevertheless, the model assumes further technological development. In the Arctic context, these are considered to be hydropower, wind, and PV technologies [1] [33]. The model focuses on wind and PV technologies, which can be integrated in various steps allowing for different transition pathways and integration strategies. Moreover, wind and solar energy are widely available to Arctic communities [34] [35]. Hydropower is excluded on the grounds that it is more challenging to implement—that is, it requires unique geographical settings, and stepwise integration is typically not cost-efficient.

Climate change is assumed for the scenarios, and a 2°C temperature increase up to the end of the century was selected following the prediction in the IPCC report ‘Climate Change 2021: The Physical Science Basis’ [32]. Moreover, it is essential to state that no feedback is assumed to change the 2°C prediction from IPCC, due to an increased renewable energy share, which slows down climate change, owing to Arctic communities’ typically small size. However, the connection between climate change and renewables would be relevant for large-scale energy transition models, given that climate change is linked to the public opinion on the promotion of renewables.

Penetration level is assumed to have a maximum of 80% renewables. While a 100% renewable share would, in theory, be possible in a wind, solar hybrid system, it would require a significant amount of financing because a considerable fraction of the installed capacity is used only rarely, simply to cover peaks in demand or shortages in production [9] [36]. For the simulation, the maximum penetration of 80% renewables in the energy mix was selected, corresponding to the literature [37]. The literature reviews have already revealed isolated high penetration grids around the globe, such as the Mawson research station in Antarctica with a wind-diesel penetration level of 65% in the period 1990-1994 [37]. Cases in temperate regions report renewables penetration level of between 70% and 94% [37].

The balance represents the utility company’s liquidity. The model aims to keep the account positive. The account’s limits can be selected. If the account becomes negative, the models initiate actions aimed at returning to a positive state by changing the electricity pricing strategy. The electricity pricing strategy will also be adjusted if the savings increase. The fieldwork demonstrated that utility providers may be either community- or state-owned in several Arctic communities. It is assumed that the utility company works sustainably but is non-profit oriented. Electricity pricing is one of the model’s key outputs. The price variable

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[2] This approximately represents the average size of the communities in the field study, Longyearbyen, Maniitsoq and Kotzebue.

is tracked for the purpose of determining how the cost burden for the end consumer is affected by the introduction of renewables.

Investment in renewables represents the amount of money that is invested in acquiring the renewable energy generation infrastructure like energy generation equipment and energy storage equipment, to fulfill the policymaker's targets on renewables´ installed capacity. It also represents investments made with the aim of replacing renewable energy generation infrastructure after its lifetime has ended.

Subsidies for renewables represent the amount of investment in renewables that is subsidized by policymakers. The money may be allocated from CO_2 tax, revenue tax, or external funding, among other sources.

A wind to PV ratio of 40% was selected on the grounds that it was proven suitable in a preliminary study. The percentage of PV is lower as a result of the significant seasonal impact. Moreover, it should be noted that the value focuses on the installed capacity. Owing to the different capacity factors, the electricity that PV generates accounts for less than 40% of the electricity mix.

Table 1. Input variables and parameters. The type denotes the input behavior. Type = variable means that the value of the input parameter changes over time following a pattern that the user gives. Type = initial indicates an input variable, where the value of the variable is given for the first period and calculated by the model for the remaining periods. Type = fixed means that the value of the parameter is used throughout all time steps.

Variable	Type	Value	Unit	Source
CO_2 price	variable	20-50	$/t	[38]
Cost Battery	fixed	3,640	$/kW	[39]
External funding for subsidies	variable	25,000	$	user
Inflation rate	fixed	2	%	[40]
Interest rate	fixed	5	%	[41]
Max RE penetration	fixed	80	%	[37]
Ration Wind PV (% of PV)	fixed	40	%	user
Unemployment rate	initial	12.2	%	[42]
Money generated by jobs	initial	2,500	$/month	[4]
Population	initial	3,150	people	user
Energy Demand	initial	23,825	kWh/day	field visit
Diesel Capacity factor	fixed	28	%	field visit
PV Capacity factor	fixed	25	%	field visit
Wind Capacity factor	fixed	33	%	field visit
Diesel Generator Cost	fixed	800	$/kW	[43]
Diesel Fuel Consumption	fixed	0.25	liter/kWh	field visit
Fuel Price	initial	0.85	$/liter	[44]
PV Installation Costs	fixed	3,000	$kW	[33,45]
Wind Installation Costs	fixed	2,500	$/kW	[9,46]
Diesel O&M Costs	fixed	0.2	$/kWh	[47]
PV O&M Costs	fixed	9.1	$/kW	[48,49]
Wind O&M Costs	fixed	3	%	[50]
Climate Change	variable	0-2	°C	[32]

4.3.3. Sub-systems

The model has three sub-systems: energy generation, economy, and policy. In the following, a CLD for each sub-system will be represented. The CLDs constitute simplifications of the model for the purpose of demonstrating the feedback between the model's main aspects.

Energy generation: This part focuses on the different energy generation technologies, which are well proven under Arctic conditions; wind, PV, and diesel. Hydropower is well established but excluded, as explained in the section entitled Assumptions and Key Variables. In this part, the cost of energy generation, installation cost, and emissions will be evaluated. The energy generation sub-system is a linear model. The sub-system provides the input for the economic sub-system. As Figure 2 illustrates, the energy sub-systems will be fed with technical data, energy economic data, and energy demand of the community. Under technological input, the given input is processed, and the energy demand per technology is calculated. The generation and investment costs per technology are calculated in the next step. The main outputs are the investment cost in technology and the electricity generation costs. Therefore, the model calculates how much capacity must be created and estimates the installation costs and the cost of generating energy.

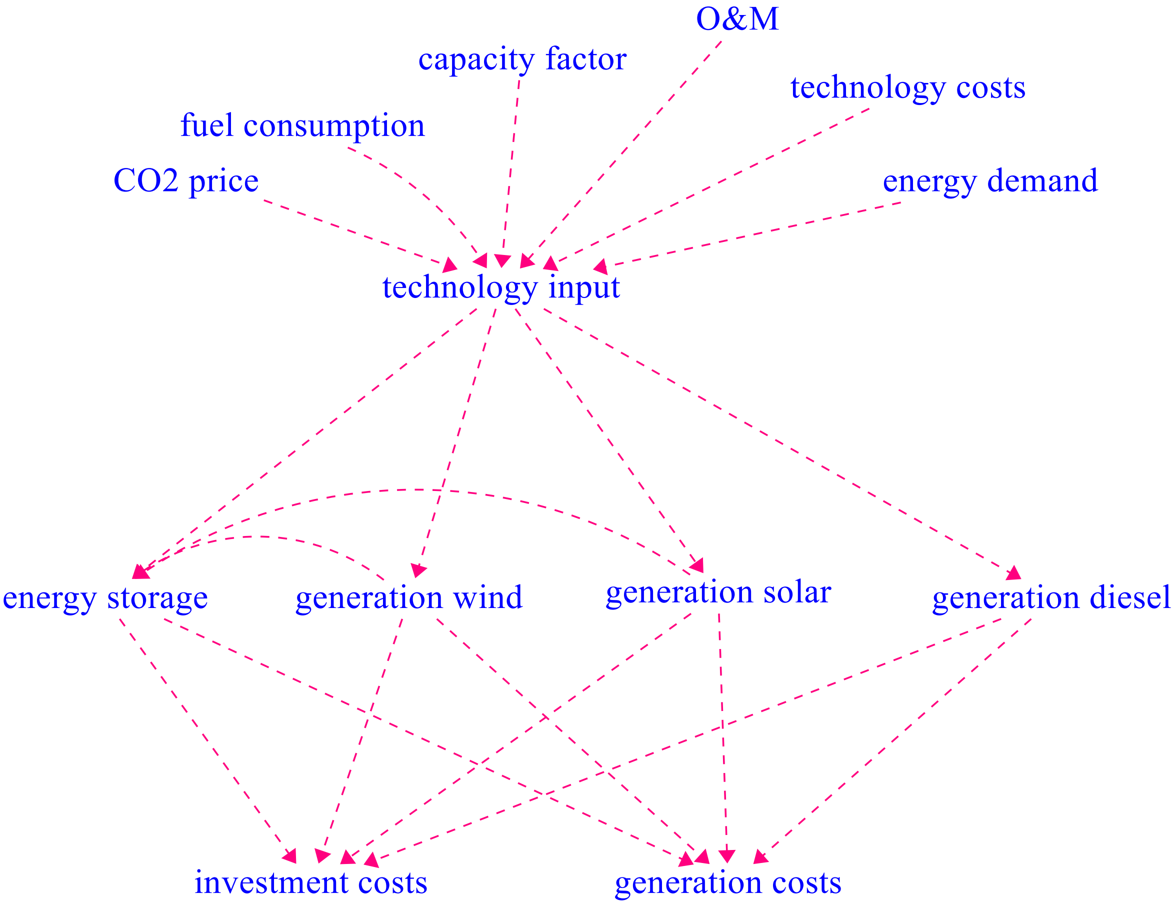

Figure 2. The energy generation sub-system compiles the technology input for the economic sub-system. It is a straightforward sub-system that arranges the technology part in accordance with the external input. For the calculation, all input variables and the given energy demand per technology are bundled under technology input. The technology input is divided among the different technologies. The technology-specific section includes the investment costs and generation costs per technology calculated and combined as output for the economic sub-system.

Economy: This part may be divided into a general microeconomics model and the energy provider's microeconomic economic behavior. The general economics part evaluates the energy demand resulting from residential and commercial needs, as represented in Figure 3. This sub-system will analyze how different employment scenarios and demographics affect energy demand. The energy provider part analyzes the electricity sales price in loop B1 in Figure 3 based on the assumption that the energy provider is operating sustainably and the operation cost of the energy-providing infrastructure is ensured. The model thus uses electricity generation costs and seeks to determine the price that the operator requires to perform sustainably. Performing sustainably means harmonizing the core business's social, environmental, and economic aspects. Therefore, model constraints allow the operator to keep a certain amount of money in his bank account for re-investment but not to maximize profit, therefore the consumer price of electricity can be lowered. If the bank account falls below that safety line, electricity prices will be increased. Alternatively, the electricity price will be reduced if the electricity provider goes beyond a limit. The nature of the model is to increase the share of renewables which covers the aspect of an environmental goal in the company's philosophy. Sustainable performance was selected because several remote utility providers are community or state-owned. In the specific case the model aims to harmonize the environmental aspect by increasing the use of renewables, the social aspect by offering as low as possible electricity prices and the economic aspect by giving the utility company liquidity to operate.

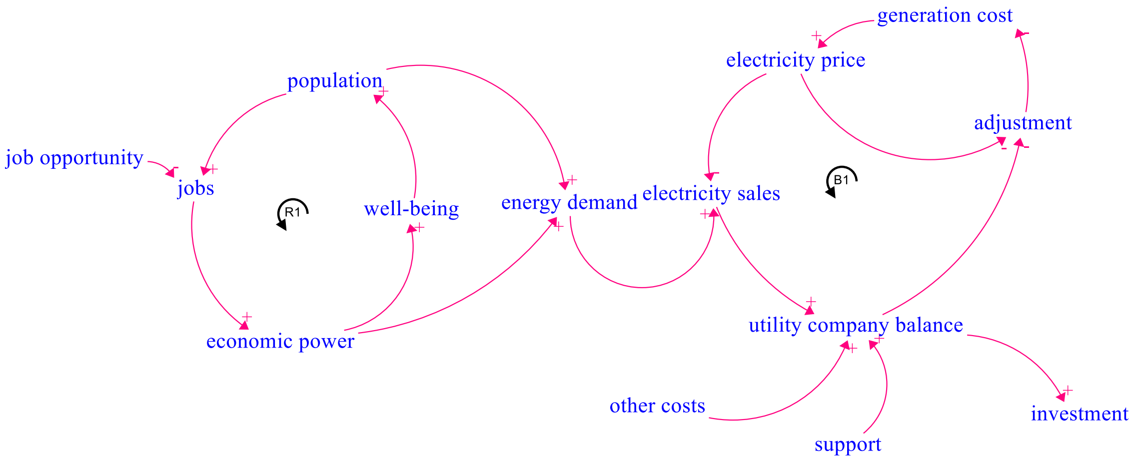

Figure 3. The economy sub-system has two loops. One loop represents the local economy, and the other loop represents the utility company and its pricing strategy. The key variables are energy demand, which provides sales feedback, and the energy generation sub-model. The main input is the generation cost, as derived from the energy generation sub-model. Electricity sales price is the main output.

Policy: This part of the model creates different strategies for the implementation of renewable energy. The main feature of the sub-system represented in Figure 4 is loop B2, which describes how public pressure impacts policymakers and may cause renew-able energy penetration levels to change. Climate change and inhabitants' sensitivity to climate change are key driving inputs, pushing local decision-makers to support the transition process. Political actions slow the transition as a result of delays in the decision-making process. The second main feature focuses on subsidies, which may be financed by a CO2 tax, external funding, or percentage of tax revenue. It also focuses on how much money will be made available to support renewable energy, which is linked to the actual subsidies available for the construction of renewable energy infrastructure.

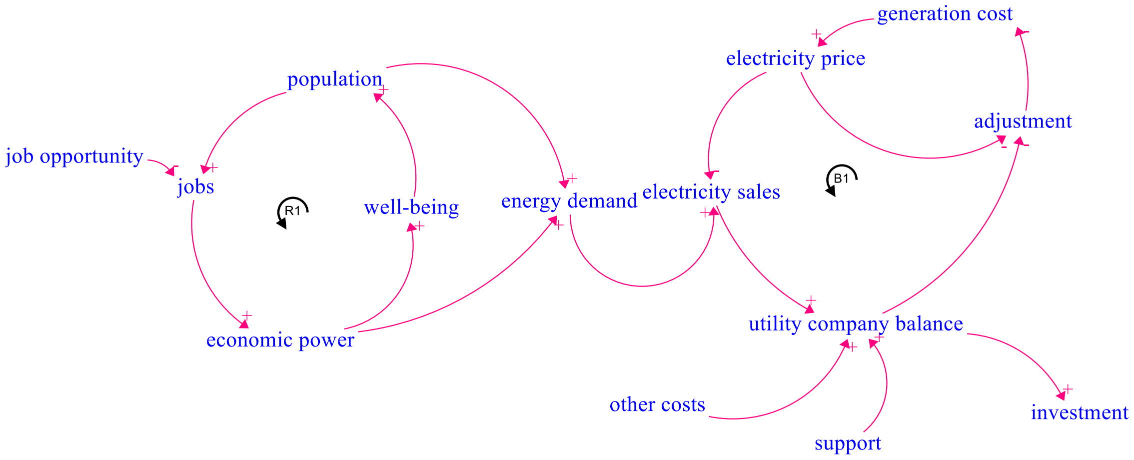

Figure 4. The main function is loop B2, which represents the integration of renewables. Another feature is the subsidy mechanisms in the sub-system, which will be used as an external input for the economic sub-model.

4.3.4. Model Validation

The first step in the model validation was to examine the internal logic. The model, its basic behavior, and resulting behavior were compared to the behavior reflected in data collected from interviews and the literature. In the second step, a historical fit analysis was conducted. The model was initially fed with existing data from a field study community and examined with respect to how well the model results fit the actual behavior over time. However, gaps emerged in the historical data of the field study communities. The output of the model and real-world data showed similar behavior in terms of electricity price development. In both cases, a similar downward trend was observed. However, this validation method is liable for criticism on the grounds that it focuses on the past while the model is designed to offer predictions regarding the future [18] [19] [51]. In a third step, an extreme value analysis was also performed to further enhance the model's validity. Therefore, parameters were fed with exaggerated values to allow the prediction of a reaction that could be compared with the model's reaction [15] [51]. As Figure 5 illustrates, three different extreme values were tested for the extreme value analysis: unlimited and free financial recourses, no renewables at all, and a high push for renewables. As predicted, the integration occurred quickly in the case of unlimited financial recourses, and the electricity price dropped swiftly as a result of the reduced generation costs. The price drop was predicted on the basis that all installation or replacement costs incurred by the generation facilities are covered by subsidies and thus do not affect the utility company's balance. In the second case, with no renewables, it was predicted that the electricity price would increase in tandem with fuel price increases, CO_2 tax, and inflation. The model showed the same result as in the first case, with some spikes. A closer look at the energy provider's balance indicated that the spikes resulted from the provider's pricing strategy and the strategy of maintaining the bank account within specific boundaries. As predicted, the third case, with no subsidies and a swift transition, as predicted, revealed a high increase in electricity costs followed by a significant decline. After the various validation methods had been completed, the model indicated that it is capable of representing energy transition for Arctic communities, according to the information collected in previous research steps.

A preliminary study that implemented a simplified version of the model was used to conduct a sensitivity analysis with the aim of determining the impact of fuel and CO_2 price changes. The study demonstrates that the transition is initially sensitive to price changes, higher prices would increase the integration of renewables, while lower prices would slow down the transition [52]. Over time, the impact of changes in price would decline in response to the increased share of renewables. The renewables would reduce fuel consumption, which would in turn reduce the impact of fuel costs and create an energy independence.

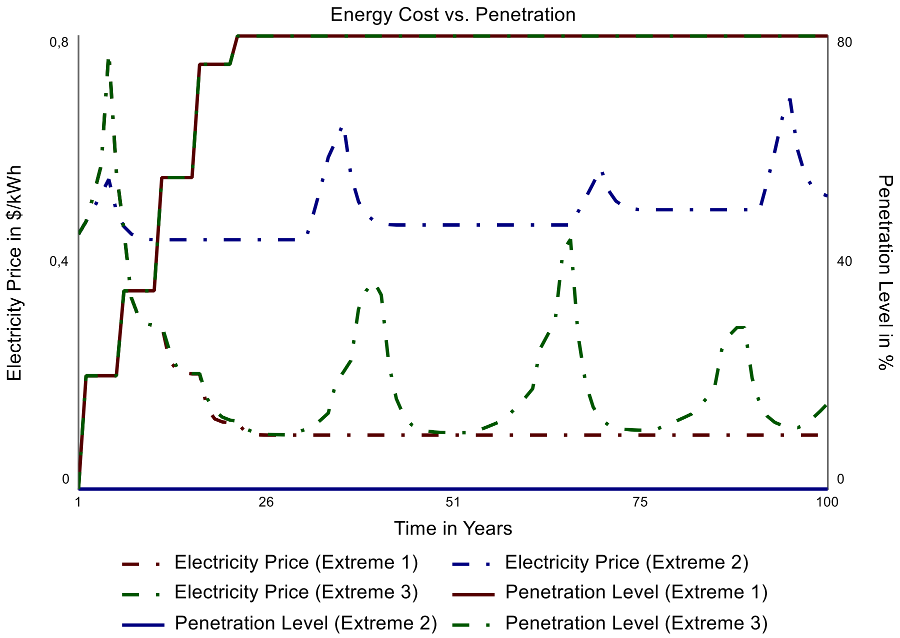

Figure 5. Renewables' penetration and electricity prices' response under three extreme conditions. Extreme 1: high public pressure and unlimited financial support; Extreme 2: negative public pressure and unlimited financial support; Extreme 3: high public pressure and no financial support

4.2 4. Results

In this section, the differences between the various scenarios and the cases' structure are explained. The base scenario and the three policy scenarios presented in Table 2 were designed to analyze the different integration strategies and environments in which renewable energy might be implemented.

Table 2. The scenarios show the different integration strategies which use different financial tools to stimulate the energy transition.

	RE penetration	CO_2 tax	External funding
Base Scenario	no	no	no
Scenario 1	yes	yes	no
Scenario 2	yes	yes	yes
Scenario 3	yes	no	no

As Table 3 indicates, a set of four cases were created for each scenario to analyze the different strategies available for integrating renewable energy into the energy mix. . In the Result section, the scenarios are simulated over a 100-year time horizon to demonstrate the electricity price's long-term behavior; as the simulation time progresses, the uncertainty increases.

Table 3. The structures of the different cases used for evaluating each scenario. The starting point can vary; early means a direct start, and late means the energy transition starts at a later time. The starting point is the result of initial public pressure. Speed denotes relatively how swiftly the renewables are integrated, which depends on the inhabitants' sensitivity.

	Start	Speed
Case 1	late	slow
Case 2	late	fast
Case 3	early	slow
Case 4	early	fast

4.3.1 Base Scenario: Business as usual

The base case represents the scenario whereby diesel is used exclusively in most communities. The model's driving force is expected to be the increase in fuel cost [11]. Given that no renewable energy is added to the mix, the penetration level of renewable energy in Figure 6 is at zero.

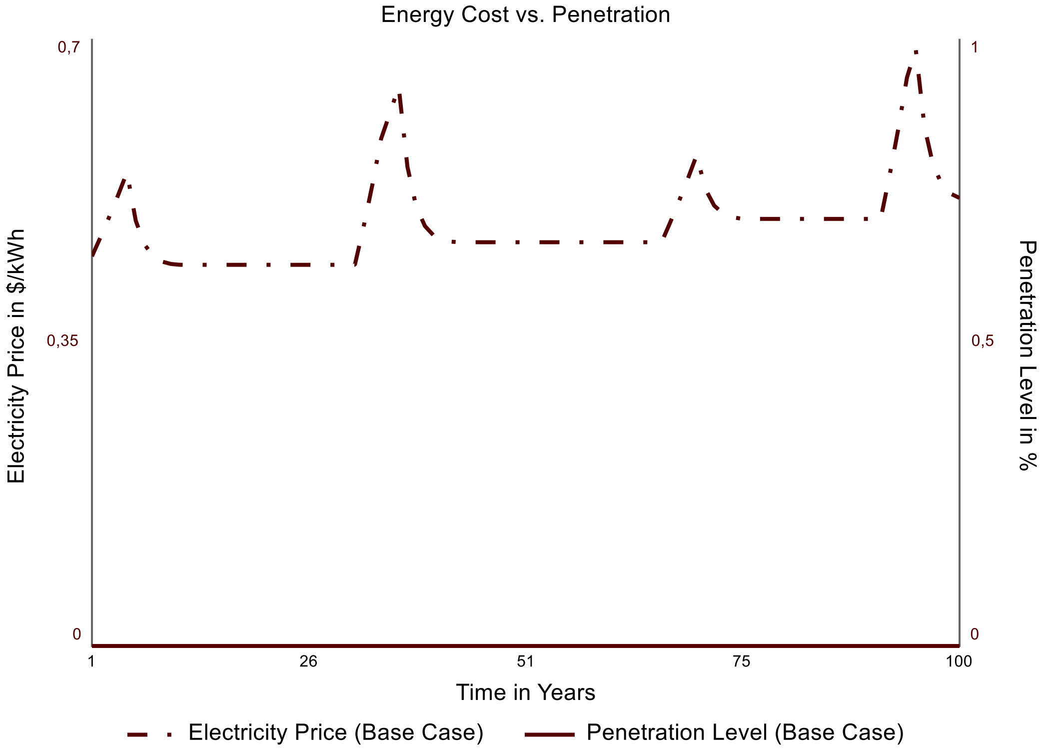

Figure 6. The energy price for the business-as-usual case. The first peak occurs because the simulation starts with no money in the utility company's bank account and some funds for repair and re-investment is needed. The three subsequent peaks are the result of diesel engine replacement. The penetration level remains at zero throughout the entire period.

The first peak in Figure 6 results from the model's assumption that the energy provider's bank account is zero, as can be seen in Figure 7. The SD model aims to create financial security by creating savings for the utility provider, which is the reason for the initial peak. The three peaks at time steps 30, 60, and 90 result from renewal of the diesel generators. Literature and field visits have revealed that outdated diesel generators are widely used [53]. This may be attributed to several reasons. First, the rate at which diesel engines age depends largely on the number of times they are started and their operation time [36]. In Arctic communities, the use of a set of generators within a rotating system results in fewer operation hours per generator. The rotating system is one reason for the low capacity factor in Table 1. New generators are often more complex, and no adequate workforce is available [54].

Figure 8 illustrates the investments for the replacement diesel generators. The resulting electricity price of the model shows an upward trend, and the driving forces are the fuel price increase and general inflation. The energy provider performs sustainably and can cover the investment cost in new diesel generators for savings. As Figure 7 illustrates, loans are required to cover the investment at timesteps 30 and 90.

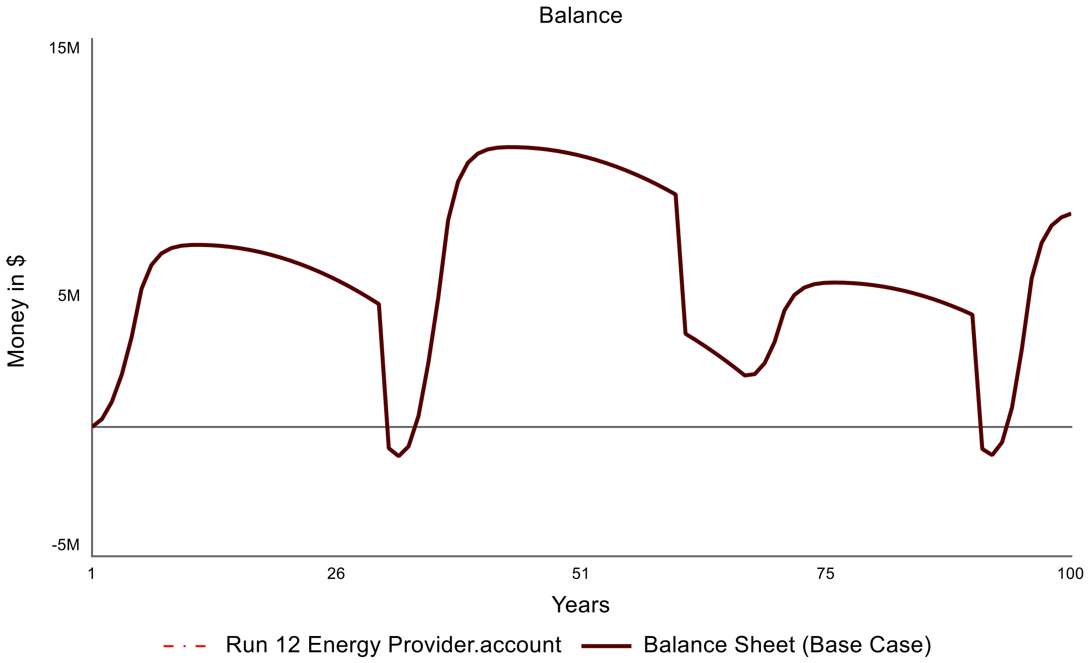

Figure 7. The balance of the utility company account in $, which shows the three troughs resulting from the investment in new diesel generators. Each plateau's slight decline is the result of inflation.

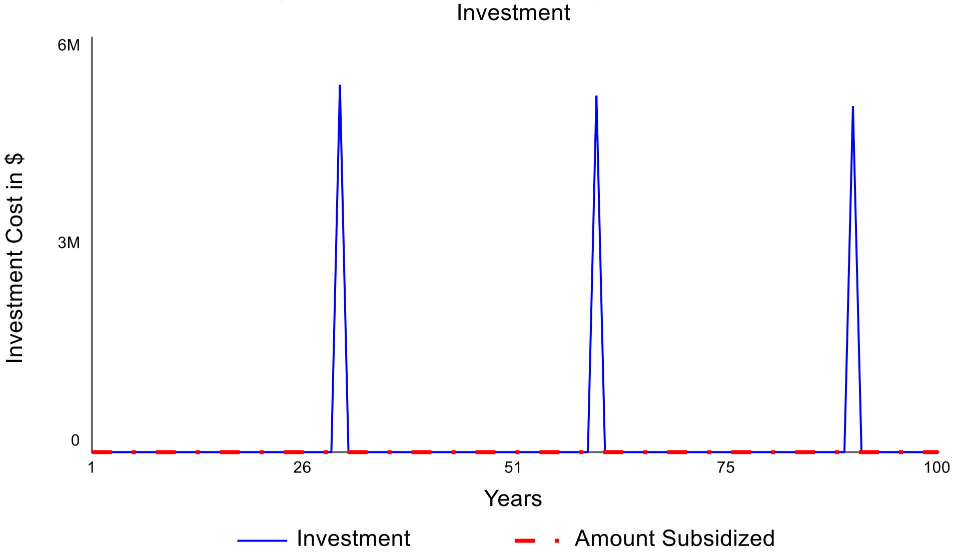

Figure 8. No subsidies for the investment is indicated by the red line. Only three investments are made for new diesel generators, indicated by the blue line.

4.3.2 Scenario 1: CO2 Tax

The first scenario uses the introduction of a CO2 tax as a policy instrument to stimulate the transition towards the use of renewable energy, by allocating the income of the CO2 tax toward subsidies [38]. Cases 1 and 2 include no initial pressure, allowing the policymaker to wait and see. This wait-and-see behavior is assumed to help policymakers set aside some savings that will hopefully allow them to act faster and pro-vide more support should public pressure intensify. Cases 3 and 4 include some initial pressure to which the policymakers respond immediately. In all cases, no other external funds for subsidizing are available but only regular loans.

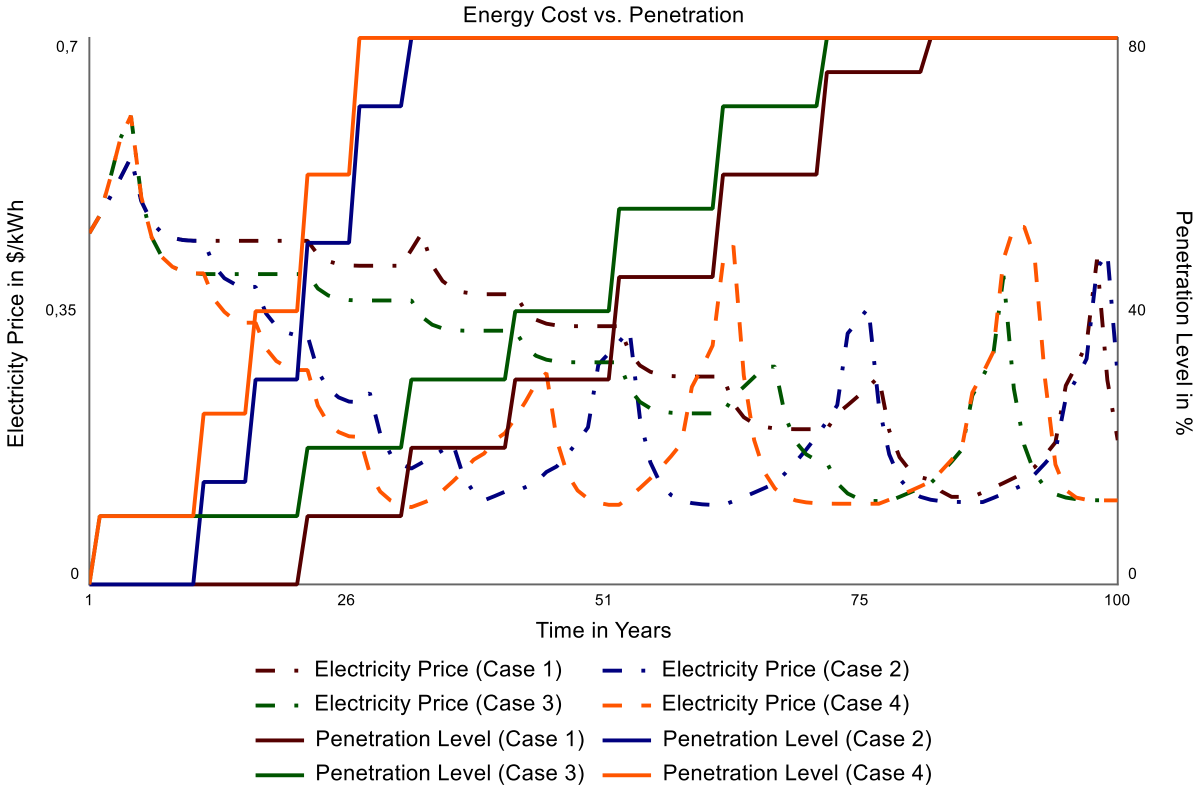

Figure 9. Energy costs vs. renewables' penetration levels. The penetration level results from public pressure and policy, and the electricity price is the result. The solid lines represent renewables' penetration levels, and the dashed lines represent the electricity prices.

Figure 9 shows different integration cases of renewables. The solid lines represent renewables' penetration levels as the results of different integration strategies. The penetration level is contingent on the degree of public pressure experienced by policymakers. The influence exerted by public pressure on decisions increases with greater sensitivity to climate change. Consequently, public pressure defines integration speed and the patterns that characterize the introduction of renewables. Case 4 shows the fastest integration of renewables (solid orange line), followed by case 2 (solid blue line). The dash–dot lines in Figure 9 represent the electricity prices for the different renewable integration cases. A glance at the corresponding electricity prices (dashed lines) reveals that cases 2 and 4 perform similarly in terms of electricity prices, while case 4 performs on a slightly lower electricity prices. Cases 1 and 3, which show slower renewable integration rates, have slightly higher electricity costs on average than cases 2 and 4. Case 3 has a lower electricity price throughout the entire simulated period.

Electricity prices will increase within the first five years following the initiation of the integration process, before electricity prices decline and dip below the initial price. The well-known worse–before–better situation results from the assumption that the energy provider begins with no capital reserves [15].

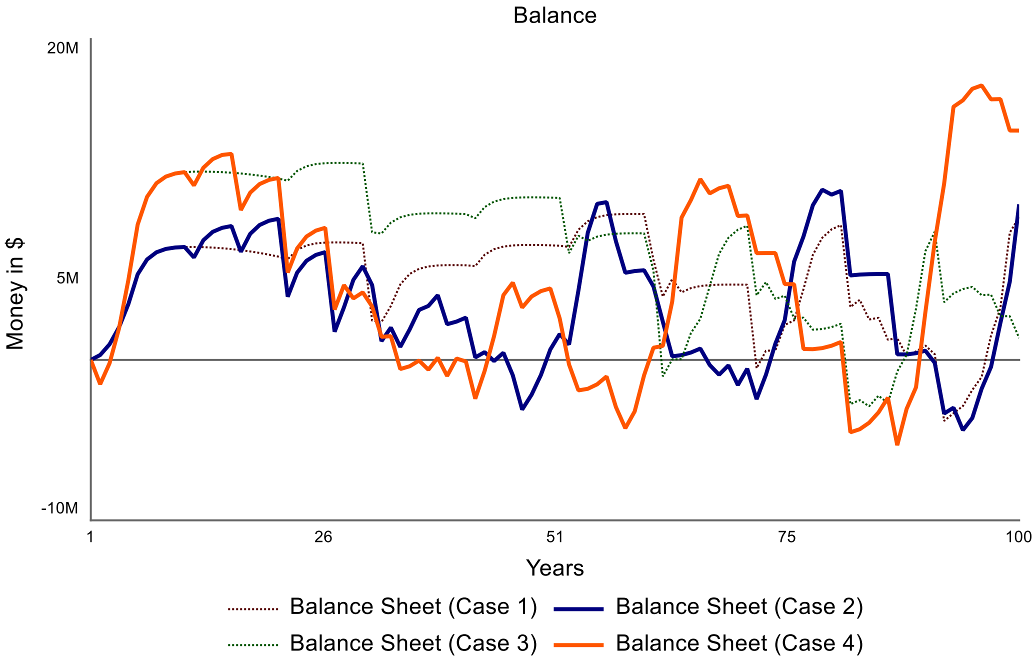

Figure 10. Balance of the utilities account. The solid lines represent the cases with a fast energy transition. The dotted lines represent the slow transition cases.

In the first half of the simulation, Figure 9 shows a significant decline in electricity prices, represented as a dashed line. This decline correlates with the increasing share of renewables, represented as solid lines. Following the increase in the share of renewables was increased for a step, the electricity price dropped after a delay. Figure 10 represents the energy provider's balance, revealing that cases 2 and 4 and cases 1 and 3 show similar behaviors, albeit on different baselines. The spikes of the electricity price in Figure 9 correlates with loans that the energy provider was obliged to take out, which are represented in Figure 10 by the negative balance. If the balance is negative, money must be loaned, and interest must be paid. The energy provider's balance clearly shows several sudden drops. A look at the investments for renewables represented in Figure 11 reveals that the spikes in electricity prices in Figure 9 are the results of investments. These investments may represent the integration of renewables, or the replacement of already-installed technology at the end of its lifetime.

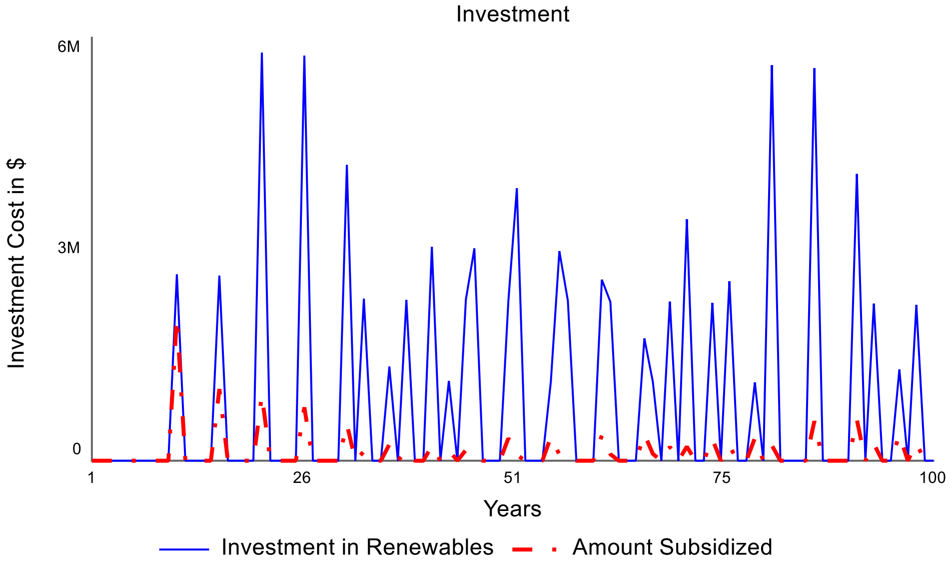

Figure 11. Investment and the amount subsidized. At the top is case 2, with the highest public pressure.

4.3.3 Scenario 2: CO2 Tax and External Funding

The second scenario examines a different set of policy instruments. In particular, it studies how a CO_2 tax and external funding for additional subsidies influence the transition process. As in the first scenario, there are four cases. In cases 1 and 2, the initiation of the energy transition process is delayed, while in cases 3 and 4, the transition process begins directly. Moreover, cases 1 and 3 show a slow transition, whereas cases 2 and 4 appear to introduce renewables more quickly.

Figures 12 and 13 illustrate trends that are similar to those that emerged in the first scenario (Figures 9 and 10). The additional subsidies result in lower electricity price peaks after the integration target has been reached. The electricity price spikes result from investments in renewables, which are lower than those in scenario 1. The lower spikes are the result of a different subsidizing scheme. In scenario 1, the income from the CO_2 tax is allocated to investments in renewables. As the renewables' penetration level increases, the proportion of diesel declines, resulting in a lower income from the CO_2 tax, even if the price per ton of CO_2 increases, as the Organisation for Economic Co-operation and Development's (OECD) CO_2 tax prediction assumed [38]. In the second scenario, the income from the CO_2 tax and an annual income from external sources may be allocated to investments in renewables.

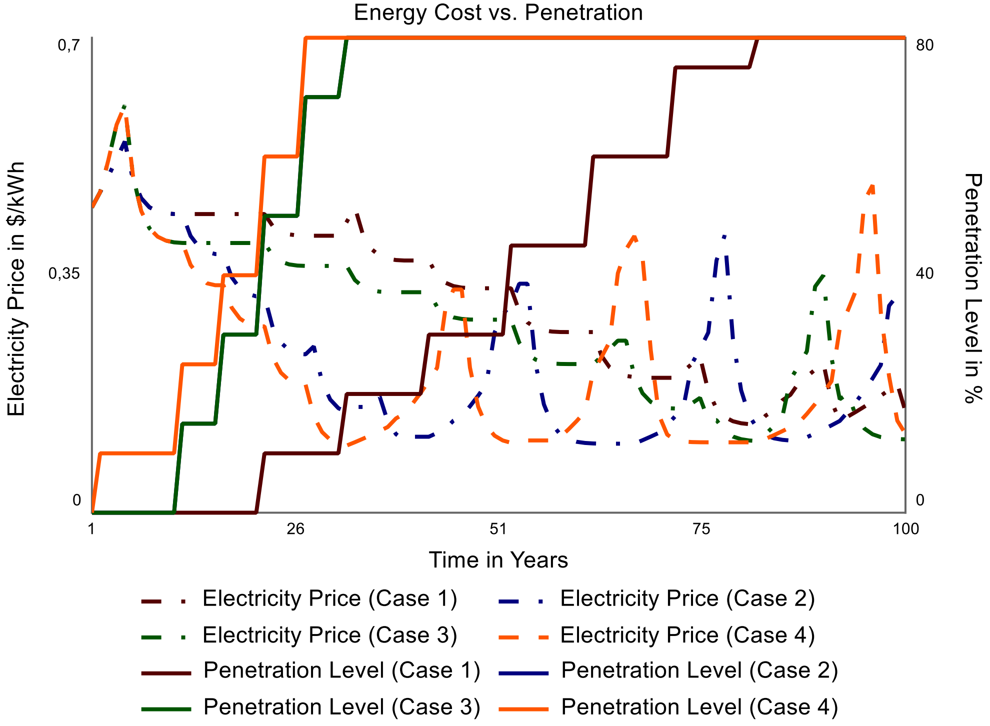

Figure 12. Energy costs vs. renewable penetration levels. The penetration level results from public pressure and policy, and the electricity price is the result. The solid lines represent the renewables' penetration level, and the dashed lines represent the electricity costs.

As in the first scenario, the savings on the balance in cases 1 and 3 and the savings in cases 2 and 4 show similar behavior, as Figure 13 illustrates. The main difference is that the curve is shifted slightly upwards, indicating that the company requires fewer loans to finance the transition.

Figure 14 shows the investment and subsidy for cases 2 and 4. In case 2, the subsidies are higher for the first four investments than they are for case 4. Compared to the first scenario, after time step 25, more subsidies are available in the second scenario at the same time step, as the CO2 tax's impact is diminished.

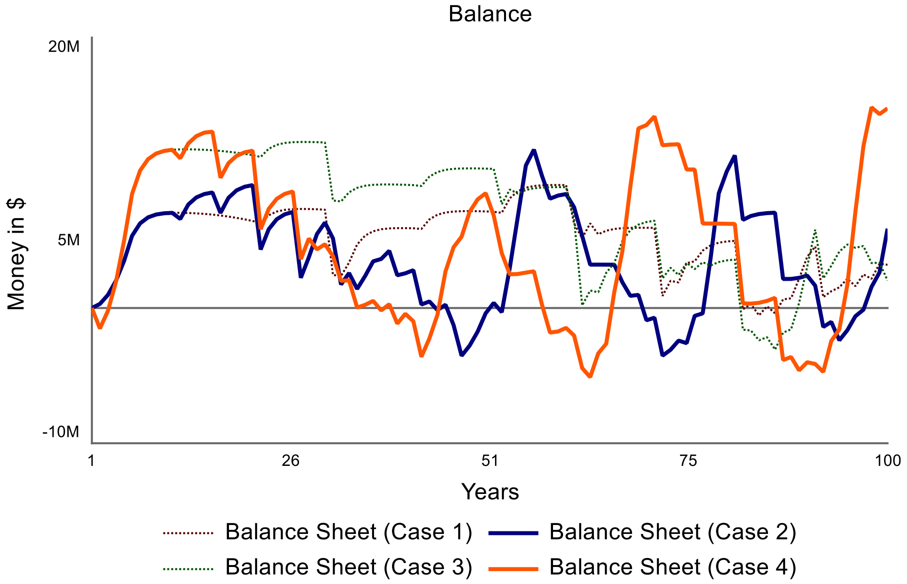

Figure 13. Balance of the utilities account: the solid lines represent the cases with fast energy transition. The dotted lines represent the slow transition cases.

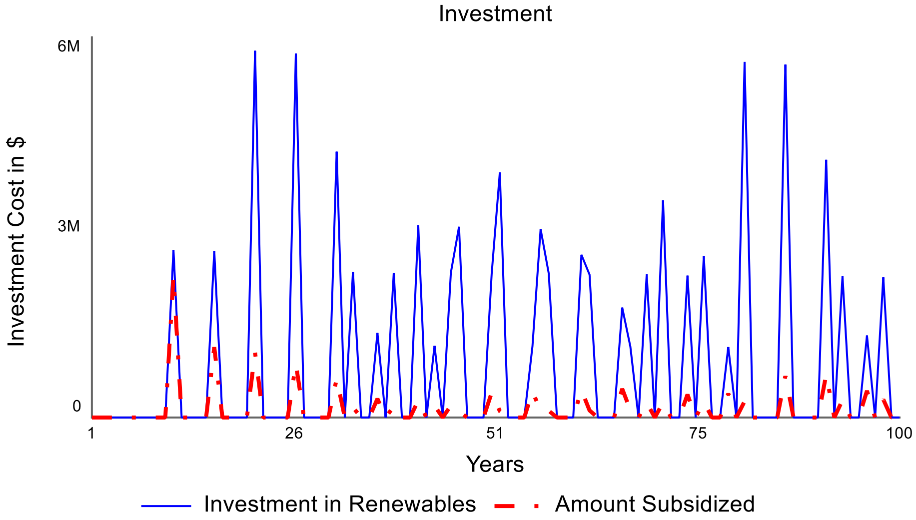

Figure 14. Investment and the amount subsidized. At the top is case 2, with the highest public pressure.

4.3.4 Scenario 3: No Support

The third scenario examined how the energy transition would look if no financial support was provided amid a push to introduce renewables. Scenario 3 could lead to a situation in which the energy provider is obliged to invest a significant amount of money to meet the targets established by policymakers. In this case, it may be critical for the energy provider if they lack sufficient capital and no subsidies are forthcoming.

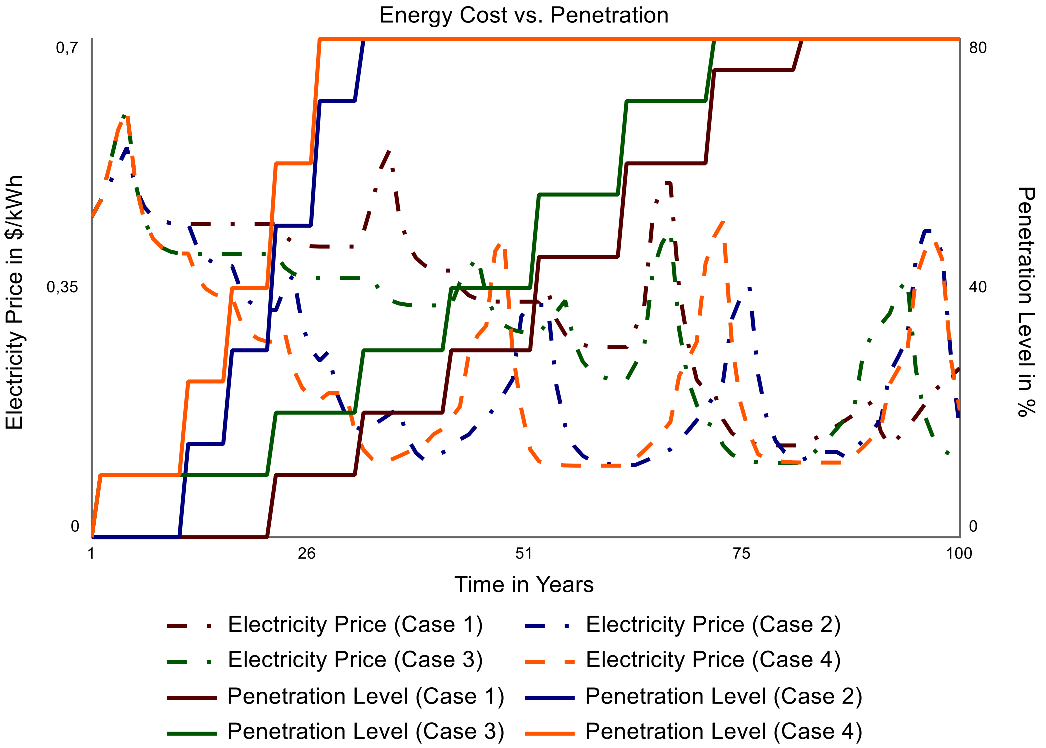

Figure 15. Energy costs vs. renewable penetration levels. The penetration level results from public pressure and policy, and the electricity price is the result. The solid lines represent renewable penetration levels, and the dashed lines represent the electricity costs.

Figure 15 shows that scenario 3 has a slower reduction in electricity prices com-pared to the corresponding cases of the first and second scenarios. Moreover, the peaks are the result of investment in renewable technology, as Figure 16 illustrates. The electricity price remains higher as in scenario 1 and 2 to avoid a trough and to allow the energy provider to operate sustainably. For all four cases of scenario 3 have a slightly higher volatility in electricity price than the corresponding cases in scenarios 1 and 2, which is evident in the electricity price. It is expected that the higher volatility is the result of the lack of financial support.

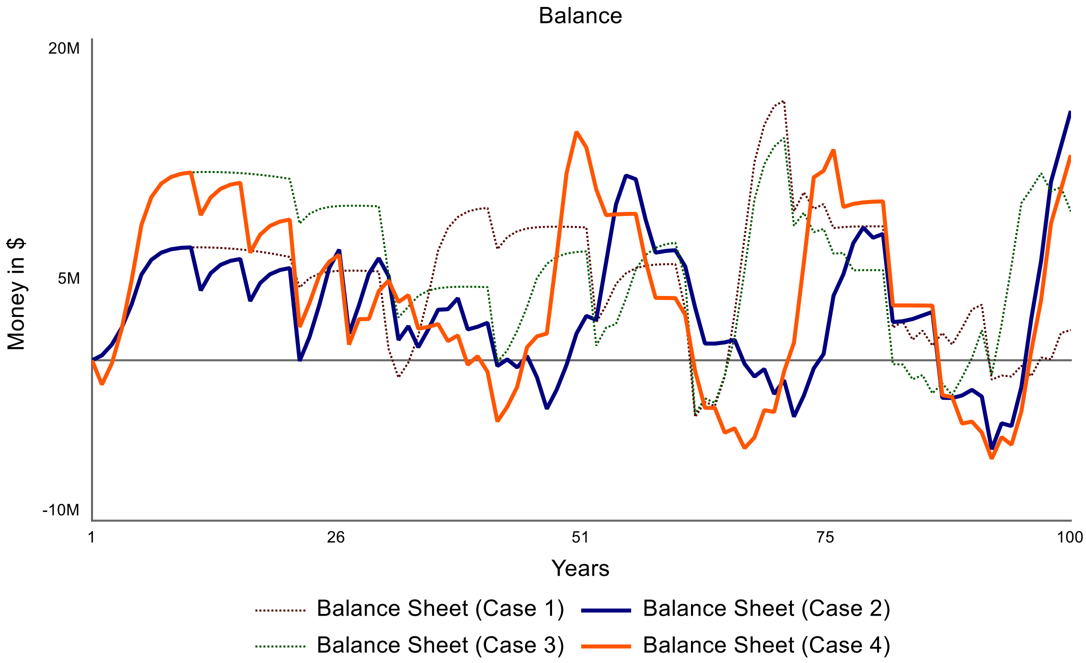

Figure 16. Balance of the utilities account: the solid lines represent the cases with swift energy transition. The dotted lines represent the slow transition cases.

4.4. Discussion

The four scenarios with different cases demonstrate that the integration of renewable energy sources in Arctic communities exhibit significant potential to reduce electricity costs. The potential cost reduction is shown in Table 4. The slope of the linear regression for all cases is negative, which means the electricity price has a downwards trend over time. The three scenarios reveal how different financial tools can support the energy transition and provide electricity prices that, in all cases, are lower than in the business-as-usual scenario. As assumed in the dynamic hypothesis the system is trapped in a path dependency and a degree of force is required to break through that dependence. In all four scenarios, a worse-before-better behavior is evident from the end consumer's perspective within the first ten years. The electricity price rises, creating the momentum required to initiate the transition process. This makes the financial situation worse for the end consumer. Following the transition, the electricity price falls to below the initial level, thus improving the situation from the consumer's perspective. As the share of renewables increases, electricity prices become increasingly independent of the impact exerted by fuel price changes. Table 4 offers a closer look at the different scenarios and associated cases' electricity prices. The results reveal a significant range in the average electricity prices across the simulated time, with costs ranging from 0.26$ per kWh to 0.42$ per kWh across all cases from scenarios 1, 2, and 3. Overall, the highest average electricity price for renewables is 0.05$ lower per kWh than the average electricity price at 100% diesel. Comparison of Table 4 with the 100% diesel case (see base scenario business as usual) reveals a significant cost saving. The average cost of generating electricity with 100% diesel would be 0.47$ per kWh, which includes the anticipated changes in diesel costs and CO_2 tax.

Furthermore, while the results show slight differences between the scenarios, the main difference is between the cases. Overall, cases 4 and 2 are financially preferable. In case 4, the transition is initiated immediately, whereas in case 2 it begins after a delay; in both cases, however, there is a swift transition, and both reach the targeted penetration level relatively close to one another. Nevertheless, case 4 is slightly more viable as a result of the marginally lower costs. Like cases 2 and 4, cases 1 and 3 differ with respect to the process' initiation, but the transition in cases 1 and 3 occurs relatively slowly, and the average electricity costs are higher. Overall, the results presented in Table 4 suggest that it is essential to conduct the energy transition within a short period of time, as in cases 2 and 4, to reduce costs. A swift transition is preferable, because it involves a greater negative slope than the slow transition cases, which leads to an earlier decrease in electricity prices. The early decline in electricity prices is better for the consumer because of the impact of interest and inflation. Moreover, the early initiation of the transition in case 4 allows the electricity price to decline even more rapidly in the beginning, which is indicated by the intercept of the linear regression. All this makes a faster transition preferable.

Table 4. Analysis of the electricity prices of all cases over a period of 50 years, which is approximately double the lifetime of renewable energy technologies. The top part shows the average electricity price. Diesel in the business-as-usual case has an average electricity price of 0.47$/kWh. The middle represents the intercept of the linear regression over 50-years. The bottom part illustrates the slope of the linear regression over a 50 year period. The trendline is defined as y=mx+b where m is the slope and b is the intercept.

	Case4	Case 3	Case 2	Case 1
	Average Electricity Price 50 Years in $/kWh			
Scenario 1: CO_2 tax	0.26	0.38	0.28	0.41
Scenario 2: CO_2 tax and external funding	0.27	0.38	0.28	0.41
Scenario 3: no support	0.29	0.38	0.29	0.42
	Intercept of the Linear Regression			
Scenario 1: CO_2 tax	0.48	0.49	0.51	0.50

Scenario 2: CO_2 tax and external funding	0.46	0.49	0.50	0.50
Scenario 3: no support	0.45	0.48	0.50	0.49
	Slope of the Linear Regression			
Scenario 1: CO_2 tax	-0.0080	-0.0043	-0.0085	-0.0032
Scenario 2: CO_2 tax and external funding	-0.0075	-0.0043	-0.0087	-0.0032
Scenario 3: no support	-0.0064	-0.0036	-0.0082	-0.0028

The findings indicate that different financial tools can support the energy transition in a positive way, as the case with no support is more costly. First, it is crucial that investment costs associated with the integration of renewables be subsidized. The subsidization can be financed, for example, through the introduction of a CO2 tax. The al-location of a CO2 tax to renewable energy projects would have the advantage of de-pending on CO2 emissions. In the event that a high penetration level was reached, the CO2 tax would become virtually obsolete given that the proportion of CO2 emitted by the vestigial generation of electricity using diesel would be negligible. Moreover, the CO2 tax will exert an additional push by increasing the generation costs for diesel generators, making renewables even more cost-competitive and fostering the energy transition [55-57]. The model indicates that the electricity prices will move in oppo-site directions. In all renewable cases, the electricity price moves downwards, while the business-as-usual shows an upward trend in electricity prices. The subsidization of in-vestment in renewables may be derived from other governmental sources, such as the allocation of revenue tax.

If no subsidy funds are available, other financing tools must be considered. Taking loans to finance large projects is one common approach. However, loans may be problematic, as interest rates for high-risk investments such as energy transition are invariably high [7]. Therefore, the government could support the energy transition process by providing the requisite security for securing low-interest loans and directly offering loans with special conditions to stimulate the transition process.

One crucial finding from all analyzed scenarios and cases is that the integration of renewables leads to cost savings for the consumers due to lower electricity prices in the long term, in contrast to the business-as-usual scenario. The reduction of electricity production costs can help reduce the household cost burden created by high electricity prices [4], which is likely to be of particular interest to regions with high unemployment and poverty rates, such as the Arctic. This aligns with the sustainable development goals (SDGs) of clean energy (SDG 7) and no poverty (SDG 1) [58]. Moreover, cleaner and cheaper electricity can help foster local business development. Clean and affordable energy is a driving economic force in different regions of the Arctic today [59-[61]. In the more specific context of remote Arctic communities, it is possible to envision a future in which competitively priced clean energy can help make the processing of local resources in local facilities more economically feasible and thereby reduce the dependence on externally located processing facilities. The development of industry in remote regions can create job opportunities and thus help those who are unemployed or in temporary employment. This would thus offer another possibility of addressing the high unemployment and poverty in many regions. Nevertheless, industrial development can also lead to negative net benefits for local communities, and this drawback must be carefully evaluated. Several questions arise in relation to various issues, including potential environmental and social impacts, such as over-tourism, pollution, greenhouse gas emissions, noise pollution from production, adverse impacts on wildlife, and impacts on social life, infrastructure, and culture. These considerations must be evaluated relative to the cost savings from renewable energy and the associated drive toward greater resource development.

There is a demand from existing and potential consumers, pushing the community's energy provider to expand or change the energy generation strategy and transit toward a greater mix of renewable energy. For example, in Maniitsoq, the interest in an aluminum smelter has given rise to plans for a hydroelectric powerplant [62-63]. While in the end, the company did not commence operations, it nonetheless highlights the connection between development and energy. For projects of this scale, it is important to evaluate the impact on the community in terms of benefits and costs, and the risks involved. The job and clean energy generation could look beneficial but how will such a large project impact local livelihoods, culture and traditions, and the environment. Another example comes from Longyearbyen, where tourism evolved before COVID-19 [64]. Eco-tourism is a hot topic for several tourism operators in the Arctic. Sustainable development can provide an essential context for discussions between local utility providers and tourism operators with respect to how tourism can be made more environmentally friendly through the use of clean or cleaner energy rather than electricity generated by coal and diesel [65]. Moreover, the airport operator has in-stalled a 137 kWp PV installation with the aim of reducing Longyearbyen airport's carbon footprint [66], which is one of the highest in Norway due to increased emissions from the electricity generated by a coal-fired powerplant [66].

4.5. Conclusion

This study has analyzed different financial tools for stimulating the energy transition in remote Arctic communities. A System Dynamics (SD) model has been developed to study the transition process towards the use of renewable energy. The SD model indicates that renewable energy has significant potential for the reduction of energy generation costs. Reduced energy costs can help reduce the cost burden among remote Arctic communities. Affordable energy is vital in low-income regions with high poverty rates, such as in many regions of the Arctic. Lower electricity costs can significantly reduce the cost of living for many people, particularly those with limited eco-nomic means, who are in temporary employment, retired, or unemployed. Moreover, sustainable energy can attract industries interested in pursuing cheap and clean electricity [65].

All the different scenarios and simulated cases revealed that renewables can help to reduce electricity costs in the long term. While substantial investment in renewables is required, communities benefit directly in the long term in the form of lower electricity prices. Moreover, the use of locally available energy sources will increase energy independence as well as primary energy security. A more general benefit will be the reduction of greenhouse gas emissions and particulate matter. To answer the over-arching question of which financial tools are favorable, the research has demonstrated that the specific method used to finance the energy transition is less important than the actual shift toward renewables with the aim of reducing generation costs. In terms of the structure of the transition pathway, it may be better to initiate the process soon-er without financial support from external sources than to wait for subsidies. Without support, electricity prices' worse-before-better behavior may be somewhat stronger, while the average electricity price will be lower than it would be during a delayed and slow transition. All cases with renewables predict a lower electricity price than the business-as-usual scenario.

Future research should carefully investigate the relationship between sustainable development and energy. At the intersection between sustainable development and energy use, it may be possible to optimize the energy transition by finding a symbiosis that fosters the energy transition. From that perspective, as noted above, renewables may be scalable to the demand side. Another exciting avenue for future research would be to elaborate in greater detail on the suitability of SD for energy transition planning in remote communities. This can broaden the horizon to other remote areas, such as South-East Asia, Africa, and Latin America. Moreover, elaborating on the method for such transition processes would increase confidence in the approach pro-posed herein.

In conclusion, this study confirms the cost-saving potential that other studies have indicated for Arctic case studies as a result of using renewable energy. However, a major novelty of this study is its demonstration of the pathways via which energy transition can be realized and financed. The key message is the importance of shifting from diesel to a more sustainable energy mix from both the economic and environmental perspectives. The simulation performed indicates that a hybrid energy system can reduce electricity prices more efficiently than an entirely diesel-based scenario, which may reduce the cost burden. Furthermore, the work has demonstrated that it is essential to structure the energy transition well. A well-structured energy transition process will make it possible to conduct the energy transition in a way that is more financially feasible.

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5. Conclusion

The conducted PhD research on Sustainable Energy Supply in Rural Arctic Areas has analyzed the current energy situation among remote Arctic communities and identified which well-proven renewable energy generation technologies are currently available for harsh, remote Arctic conditions. The viability of the integration of renewables has been examined in case studies, for which a number of remote communities were visited. The final part of the thesis studies different energy transition pathways and how the transition can be done in a feasible manner.

The research shows that by far the predominant energy source is diesel among remote Arctic communities. The use of diesel is associated with risks, complex transportation, and storage, resulting in high costs and high electricity prices. Besides conventional energy sources, renewable energy sources can also be found, such as hydropower, wind power, and photovoltaic. Hydropower is the most used renewable source for electricity generation in the Arctic. Hydropower needs specific natural conditions but can provide affordable and well-regulated electricity and is more suitable for larger communities. Wind and PV power is a vast potential in the Arctic with less specific natural requirements and can provide electricity to various-sized communities. Wind and PV power performance is not regulable, requiring additional equipment to stabilize voltage and frequency if a large share of non-dispatchable renewables is integrated.

Now the question of which energy sources are available can be answered. Only hydropower, wind power, and solar radiation are available as sustainable energy sources to be used with the currently available mature technology. Moreover, a potential for tidal power has been identified, but the generation technology is not proven under Arctic conditions, and it might be critical with icebergs and sea ice. Furthermore, biomass power is available, but the slow growth in the Arctic makes sustainable use critical. However, it would be possible with imported biomass.

Currently, the largest installed capacity in the remote Arctic is diesel generators. Nevertheless, also some hydropower, wind, and PV installation can be identified. One interesting observation is that the fraction of generated electricity by hydropower is just slightly less than the electricity generated by diesel generators. The reason is that hydropower is mainly installed in larger communities and the installed capacity for diesel also includes backup capacities.

This shows that the current energy situation in remote Arctic communities has already had some experience with the integration of renewable energy sources. In the case of hydropower, it is well-established and has a long history. In addition, the performance is easy to regulate. A few wind and PV installations can be found among remote Arctic communities. The technology has a relatively young history, with an increasing share.

The analysis of the case study communities has shown that wind and PV are cost competitive compared to 100% diesel. In all analysis cases, some cost savings were achieved. Furthermore, the results indicated that starting the transition sooner rather than later is better, especially if the diesel generation infrastructure needs to be updated. Renewables can make a community more energy independent and more disconnected from fuel price changes. The interviews revealed that renewables are widely accepted among inhabitants of Arctic communities, as long as they do not interfere with the traditional lifestyle of the indigenous people.

With the aforementioned facts, the question of whether renewable energy can be feasible for Arctic communities can be answered. Renewable energy has indicated a reduction of electricity costs in the case study and the few real live cases. Furthermore, field studies have shown that Arctic communities are aware of renewables and generally accept the technology.

Financing the energy transition was studied because financial struggles are a common problem among remote Arctic communities. Therefore, different financing strategies were studied. The system dynamic model helped analyze different integration patterns for renewable energies, representing different needs Arctic communities might have; for example, speed of integration and financial capacity.

The analyzed scenarios of the financing of the energy transition shows that renewables are a cost-competitive option to diesel. Moreover, the results conclude that it is the same for many communities. However, the simulation also shows that no single solution can be used for all communities. For each community, a new analysis should be done. The system dynamics model can help find an optimal energy transition strategy.

The conducted research can answer the overarching question ‘Can renewables provide affordable energy to remote communities?’ The research has shown that renewables are currently cost competitive compared to the use of diesel in most remote communities currently. So it is possible to lower the electricity cost and lower the cost burden for inhabitants of remote Arctic communities. Even if the energy prices are lower after the introduction of renewables, electricity prices can still be high. This shows that a well-planned transition is key to getting a well-structured transition and reaching a low electricity price to make electricity as affordable as possible in remote communities.

Energy is the backbone of most modern societies. Its absence of can have dramatic consequences, which can be observed after natural catastrophes. Nowadays, in Europe, it can be seen that even the shortage and threat of absence can lead to drastic consequences in an economic, but also private context. Concerning the conducted research, it can be seen that energy plays an important role. Energy is needed to support modern life under Arctic conditions, to provide heating, to keep the tap water running, or in some cases, even to produce the tap water. The previous facts highlight the importance of energy and how much energy is connected to the daily life of community members in the Arctic. Since there are many intersections with energy, high energy prices significantly negatively impact life negatively in remote Arctic communities. The integration of renewables can potentially cut down the high electricity prices, as the research indicates. Lower electricity prices are of particular importance in areas of high unemployment and poverty. A lowering of the energy prices would make life easier, since people would not have to spend a significant portion of their monthly income on electricity.

A more holistic view of remote communities shows that electrification is becoming more important. According to IRENA, several remote communities can be found in South East Asia and Africa. These communities currently have no electricity generation in place and are not connected to an electricity grid. We believe the results can also be of use for such communities. Even though the climatic conditions are very different, these communities might also benefit from such a transition. They have not yet installed diesel, so they have no path dependency. In the case of electrification, it might be advisable to integrate directly renewable energy sources into the energy mix. The study can indicate ways in which a potential energy transition could be structured and financed.

Overall, the study shows that the integration of renewables looks promising, even under the harsh environmental conditions, the remoteness of the Arctic, and the problems of financing the transition. Even under extreme conditions still, some potential cost reduction can be achieved. Next to the technical and financial parameters, the inhabitants of remote Arctic communities must be willing to undergo the energy transition. The study indicates that there is a general acceptance; nevertheless, it is essential to integrate the people in the community into the transition process. This might allay come concerns about the technology and will create a wider acceptance.

5.1. Outlook

This PhD research has answered several research questions on the energy transition in remote Arctic communities. However, the research has also raised a few new questions and concerns which could be the focus of follow-up studies.

In the next steps, the confidence in the methodology can be reinforced to create more impact. Create more confidence in the methodology of the resulting system dynamics model by analyzing how suitable SD is for analyses such as a transition process. That will create more confidence in the model and help to promote it among decision-makers. A more in-depth literature review could do this was it was conducted for this study. The core of the research could be to compare the model which was created in this research with models based on other methodological approaches. The study could help identify the advantages or disadvantages of using SD to analyze the energy transition among remote communities. This could show some potential for further model improvement and help create more confidence.

On the other hand, the scope of the model could be extended to other areas. The model could be manipulated so that it can be used for analysing the energy transition of remote areas with no grid connection in general. Such an adaptation would make the model applicable to communities as they can be found in some parts of South-East Asia, Africa, and Latin America. The model's main new feature would be how to conduct the energy integration if no energy infrastructure is already in place. This would answer how remote communities could be electrified if there is no existing infrastructure.

5.2. Final remarks

The study has shown that the energy transition is possible and feasible under such extreme conditions as in the Arctic. To say it with the words of Frank Sinatra (New York, New York) "If you can make it there, you can make it anywhere”. But still, more research and development is needed to make renewables more available across the globe. This study has highlighted that a good integration strategy of renewables could be essential for the integration process. However, this could be adapted to other areas as well to provide clean and affordable electricity, which is the sustainable development goal 7 of the united nations.

Appendix A

Sustainable Energy for a Secure and Affordable Energy Supply: An analysis of rural Arctic communities

A.1. Introduction

Communities in the Arctic face a harsh and fragile environment [1,2]. In this environment human security needs a constant electricity supply [3]. Diesel has been the main primary energy source for electricity generation and 80% of the communities exclusively depend on diesel [4]. Besides the negative impact on the climate the use of diesel has an impact on the mid-term energy security. The short fuel transportation window can create a risk in the fuel supply chain for the next year in the communities [4,5]. Harsh Arctic weather conditions heavily influence the transportation window – barges require open sea ways for delivery and trucks need frozen rivers, stable enough to carry them [3-6]. The negative climate impacts of diesel arise from its burning. The emitted CO2 is a well known greenhouse gas and particular matter leads to a special impact in the Arctic – lowering the albedo effect [7]. The albedo effect describes the reflection of solar radiation by the white snow - a lowering in reflection increases the melting rate of snow and ice [7]. A last point is the noise emitted by the generator, which can have an impact on life quality [8].

Energy security can be classified into short, mid and long-term energy security. Furthermore, energy security can be classified in terms of the supply chain into upstream and downstream energy security. Upstream energy security refers to the security of the supply chain before the electricity generation, such as fuel and spear parts delivery. Downstream energy security refers to the energy distribution system side. The close proximity to the end-user of renewable energy resources can increase the energy security by lowering the impact of the mid-term and upstream energy security. The introduction of local non-dispatchable sustainable resources can trigger a decrease in short-term energy security. Non-dispatchable energy sources can cause fluctuation in voltage and frequency [9]. This fluctuation can result in transmission system failures [10]. Flywheels can act as a spinning reserve and secure the very short-term energy security - seconds up to a few minutes [4,11]. To react on longer short-term time horizon - minutes up to hours - several storage or conversion solutions can be used such as battery storage, hydrogen production as storage or fuel for transportation / heating and converting electricity into heat for a district heating system [12,13]. This, and a diversification of resources can increase the energy security. If one source brakes away due to a failure the others sources still can provide the basic electricity to secure the electricity supply.

This paper applies a rough cost benefit analysis to compare a set of different solutions and study how renewable energy resources can add value to the energy security. A spreadsheet based model uses cost estimations for the different technical components to calculate the approximate total cost of investment and operation. This gives an indication of a general feasibility of the different solutions to integrate renewables into an isolated grid.

A.2. Methodology

The methodology section is split into two parts: data gathering and modelling

A.2.1. Data Gathering

The data for the research was collected through a literature review. The data collection focused on mature technologies, currently available for Arctic micro-grids and the related investment, operation and maintenance cost. The already existing data (secondary data) gives a clear understanding of the costs used for the cost benefit analysis model and reflects the current status of possible solutions [14]. Studies in Arctic areas often face a limitation of data availability. Projects in Arctic areas require higher construction costs than in lower latitudes [15]. This relates to the remoteness, missing infrastructure, harsh environment and in some cases permafrost. For example, the construction of a wind turbine in the Arctic is 2 – 3 times more expensive than in southern areas [15]. The upper end of the cost range was chosen here in absence of specific costs for Arctic areas, to take into account for the extra expenses of projects in the Arctic. An overview of the collected data is in Table 1.

Table 1. Main Data Collected for the Cost-Benefit Analysis

Name	Value	Unit	Source
Diesel price	0,85	$/Liter	[16]
Capacity factor Diesel generator	0,28	%	[17]
Fuel Consumption	0,25	l/kWh	[17]
CO_2 price	20	$/t	[18]
min. price ES	10	$/kWh	Selected
current time of outage	0,5	hours	[17,19]
Installation cost Hydro	6.500	$/kW	[20]
Installation cost Wind	3.000	$/kW	[15,20]
Installation cost Solar	4.000	$/kW	[20]
O&M Diesel	0,02	$/kWh	[21]
O&M Solar	12	$/kW	[22]
O&M Hydro	2,5	%	[23]
O&M Wind	3	%	[24]

A.2.2. Modelling

For the cost benefit analysis a simple spreadsheet model was set up. The simulation considers a lifetime of 20 years, which was chosen according to the shortest expected lifetime of generation technology. Solar PV cells reach a lifetime of approximately 20 years. Other technologies have a longer lifetime. The technology options must sustain the harsh Arctic environmental conditions; a detailed analysis is in section Analysis. Electricity generation with 100% diesel was used as a base case for the simulation and very often represents the current electricity mix since it is the situation in 80% of the Arctic communities. Renewables like wind and solar cells can be used in a mix together with diesel, such a system is referred to as a hybrid system [3,25]. Diesel generators can handle different penetration levels of renewables with different extend of regulation equipment [11]. This ability of diesel is needed if non-dispatchable energy resources like wind, and solar cells are used. Their performance fluctuates, which leads to instability. Figure 1 shows the different penetration levels. Defined scenarios were done in accordance with the penetration levels. For all penetration levels different mixtures of energy sources have been assumed; each assumption was a scenario.

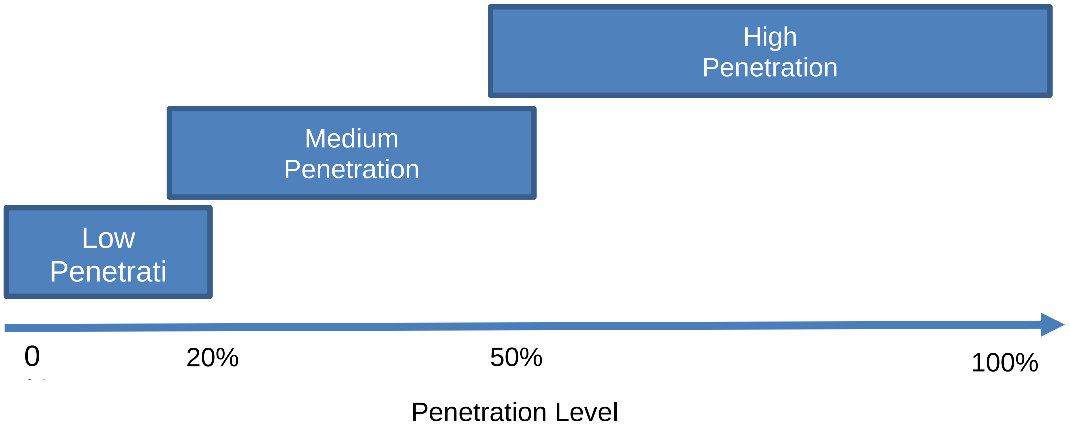

Figure 1. Penetration Levels

To encounter for the cost resulting from a lack of energy security, the value of lost load (VoLL) is calculated. The VoLL takes the economic and private loss to the society into account [26,27]. The actual value contains a multiplication of the VoLLby the average black out duration and the changed likelihood due to technology changes. The likelihood of technology changes takes the comparison matrix as a basis, Figure 2. The total scenario cost is the sum inflation adjusted net present value over the scenario lifespan.

A.3. Analysis

	Hydro	Wind	PV	Tidal	Biomass	Factor
Hydro	■	1	1	1	1	1,00
Wind	0	■	1	1	1	1,25
PV	0	0	■	1	1	1,50
Tidal	0	0	0	■	1	1,75
Biomass	0	0	0	0	■	2,00

Figure 2. Comparison matrix of generation technologies The matrix compares each technology with each other. The lower the factor the securer the technology is rated

To figure out which renewable energy sources and technologies are the most feasible for arctic communities we first do an internal ranking as shown in the comparison matrix in Figure 2. The comparison matrix shows the comparison of pairs of technologies based on their security. The assumption is that the VoLL is a lower-medium value, grounds on the low value creation per kilowatt hour in the Arctic [28]. For longer electricity supply interruptions, the consequences can lead to severe damages on infrastructure like bursting of waterpipes and no heating [19]. This life-threatening circumstance can add more value to VoLL. Since a long duration blackout is unlikely to happen the VoLL was slightly increased to a medium value.

A.3.1. Technologies

Hydropower is a mature technology with a low failure rate [20,29]. The water reservoir provides a local energy source. A dispatchable energy resource like hydropower can be a stable source of electricity to the grid. The electricity generation can be easily adjusted to the needed electricity demand [20].

A non-dispatchable energy resource such as wind cannot be regulated in terms of output performance [15,20]. Furthermore, wind power might require additional technology to stabilize the grid if the penetration is above 20%.

PV as a non-dispatchable energy resource is not a stable source of electricity either and similar to wind in that sense [20]. In addition PV shows a seasonal energy distribution with high generation potential during the summer and nearly none during the winter time [30,31].

Tidal Power in the Arctic is not a mature solution yet and the risk of damages to the infrastructure by icebergs and drift ice is considerable. Biomass technology is mature, but there is a lack of available sustainable bio resources in the Arctic. Biomass growth is barely available above the tree line in the Arctic [32], which makes a local and sustainable biomass use impossible. Imported biomass is an option to diesel but the upstream energy security issues remains.

Geothermal was not further elaborated, because of limited access among the Arctic – at the Arctic Pacific coast line and Iceland [33,34]. Geothermal has proven a very reliable energy source in the sub-Arctic conditions of Iceland [35].

A.3.2. Cost of CO2

Two different ways can measure the CO2 cost: the market value and the cost of harvesting CO2 out of the air. The CO2 market value represents the CO2 certificates value at the stock exchanges - for the European certificate a price of approximately 20 $ per ton [18]. In contrast to this carbon capturing creates much higher costs with approximately 1.000 $ per ton [20]. In this case the market value was chosen for the simulation because that is the saving companies can make in hard currency. The CO2 certificates price is expected to rise in future. Recently, several countries announced that they will not reach the targeted CO2 reduction. For example, Germany wanted to save 40% CO2 by 2020 but a current forecast estimates a saving of 32% by 2020 [36]. The CO2 cost might act as a policy leverage to increase the CO2 reduction.

A.4. Results and Discussion

Hydro power plays a critical role in providing sustainable electricity to Arctic communities. Especially if the community should mainly use renewables, high penetration scenarios as in Figure 3 are required. For all penetration levels hydro power breaks even with diesel at the end of the analysed time period, 20 years. In the scenarios a cost per kW installed capacity of 6.500 $ was assumed for hydro power plant below 20 MW [20]. The upper end of the Tester estimation has proven right compared with the actual numbers from Nukissiorfiit at the Buksefjord project [37]. A price below 6.000 $/kW or even 5.500 $/kW would help to make hydro power more affordable for smaller communities.

The introduction of renewables is heavily influenced by the cost of the CO2 as shown in Figure . An increase of CO2 prices leads to a severe reduction of the payback period. In case of a medium renewable penetration it is 6 years - calculated with an increase of 20 $/ton up to 100 $/ton for CO2. For a high penetration it is around 5,5 years and for a low penetration case 4 years. This show that CO2 pricing is a very useful tool for policy makers to support the energy transition. Moreover, the raised money can be used to help communities to cover the high initial upfront cost.

A low-level penetration shown in Figure of around 20% renewable shows that non-dispatchable energy sources can provide a feasible option to introduce renewables into the grid. The diesel generator can secure the grid stability [11]. Moreover, the diesel generators spare capacity can cover up for fluctuation in supply by non-dispatchable sources. Non-dispatchable energy sources need around 7 – 8 years for payback. The difference between solar and wind is very similar on the cost side. The installation of a hydro power plant requires an essential investment. Over the analysed period of 20 years the cost of hydro power is the same as diesel. The expected lifetime of 50 years or even longer can make it feasible. Renewables have a low cost during the operation time which gives them an advantage. Just operation, maintenance and electricity security cost are generated after the installation. Diesel has additional costs of fuel and emission. This analysis does not take into account replacement cost, because for the newly added renewables it is within the lifetime span. Since the diesel generators are assumed to be in place already they can create additional replacement costs in the observed timeframe.

Medium penetration shown in Figure , can be seen critically. The payback period is not significantly shorter compared to a high penetration level. On the investment side a medium penetration is not proportionally cheaper than a high penetration level. The problem of medium penetration is that the upstream energy security is not solved - fuel still has to be imported and just the amount decreases. On the downstream energy security side, the renewables have some added risks.

In case of a medium or high renewable penetration it is advisable to have a dispatchable energy source for the baseload and add to this non-dispatchable energy resources. In Figure an example for high penetration with a small diesel generator, wind turbines and a battery storage is shown. The case was created and checked with the simulation software HOMER. This case

shows that it is not cost competitive (green line in Figure). To provide enough energy with wind turbines the installed capacity has to be much higher than in case of a dispatchable energy source. The installed wind capacity was 5-times higher than in the 100% diesel case.
All high and medium cases have hydropower as base load. The non-dispatchable fraction reduces the payback slightly compared to just hydro power for the renewable fraction. The orange and grey line in Figure 4 or orange compared to the grey and yellow line in Figure .

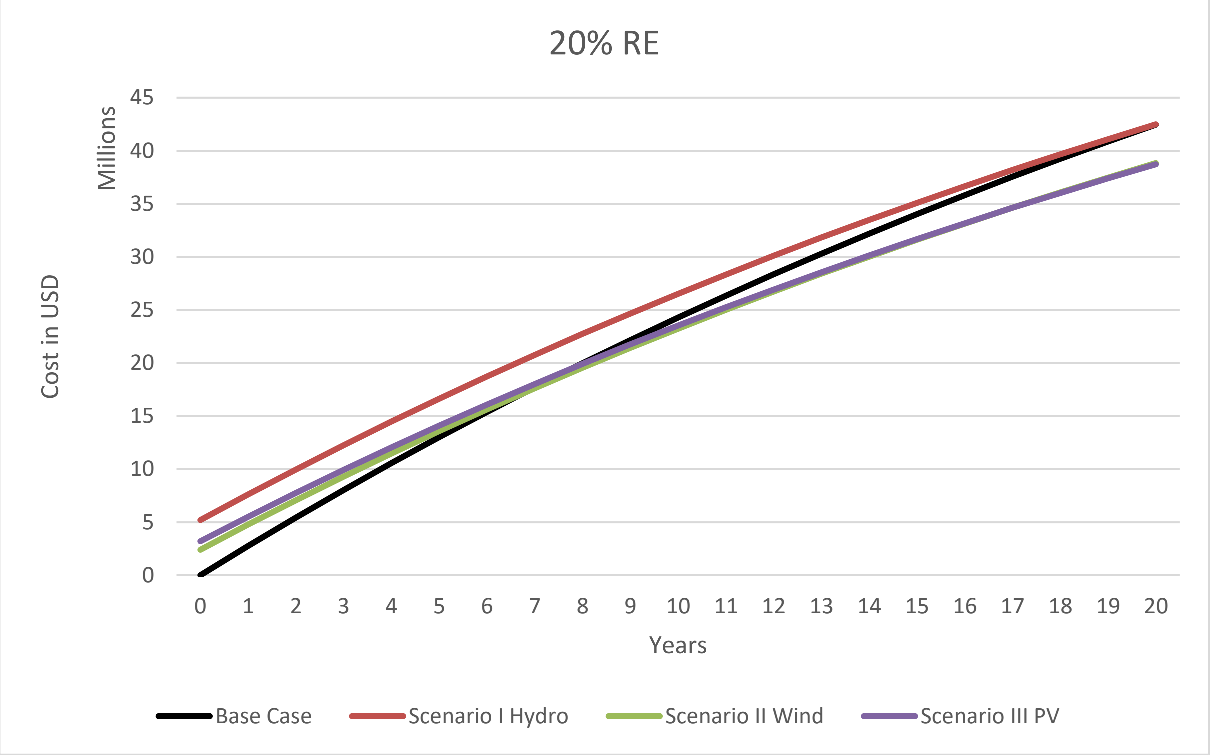

Figure 3. 20% Renewable Scenario

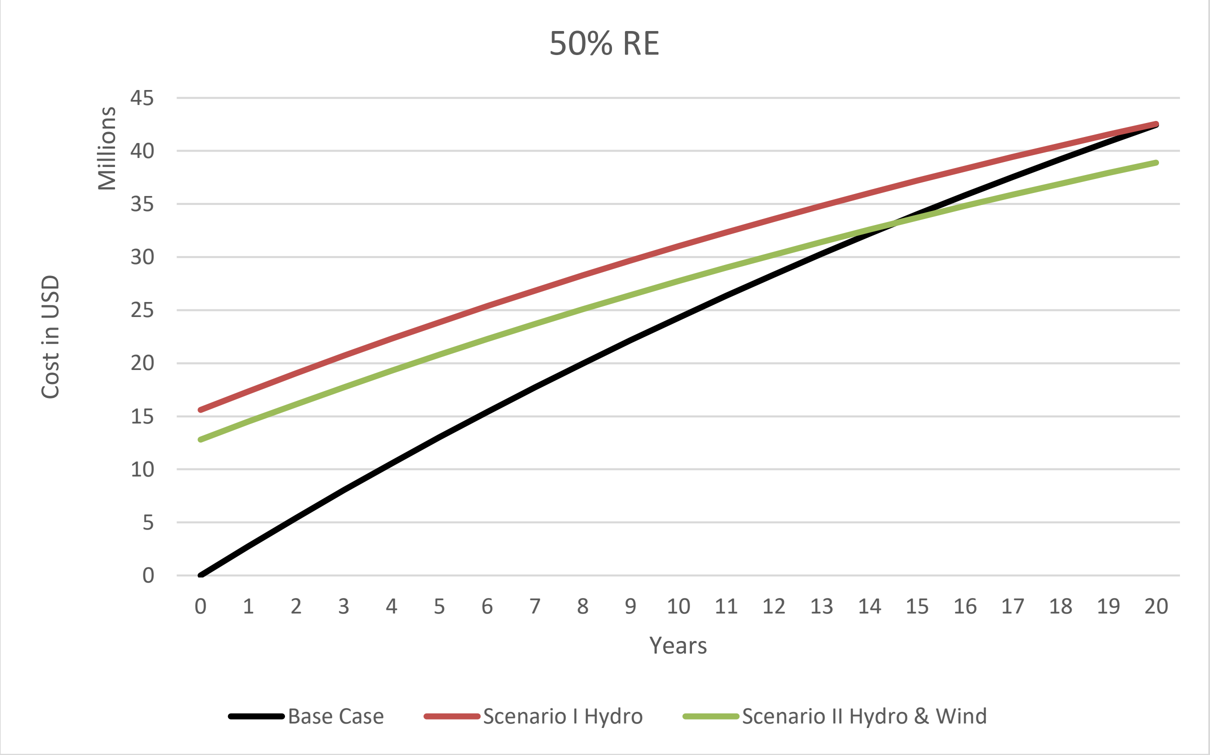

Figure 4. 50% Renewable Scenario

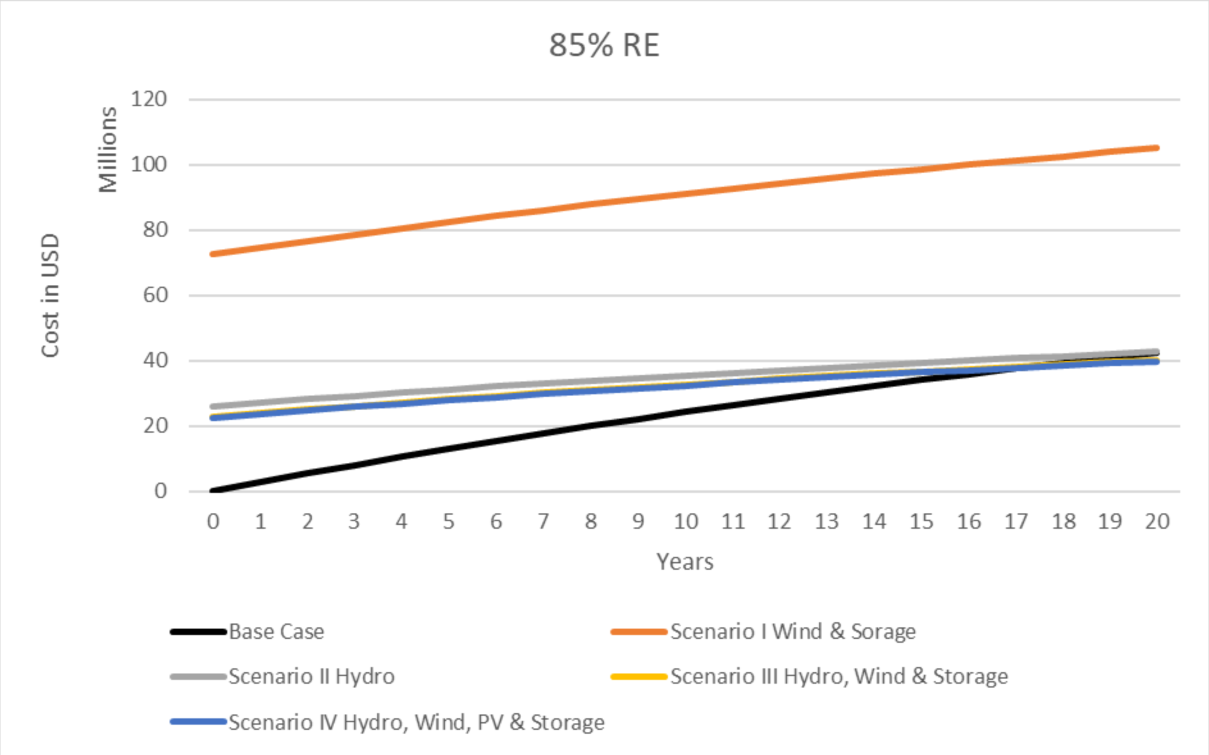

Figure 5. 85% Renewable Scenario

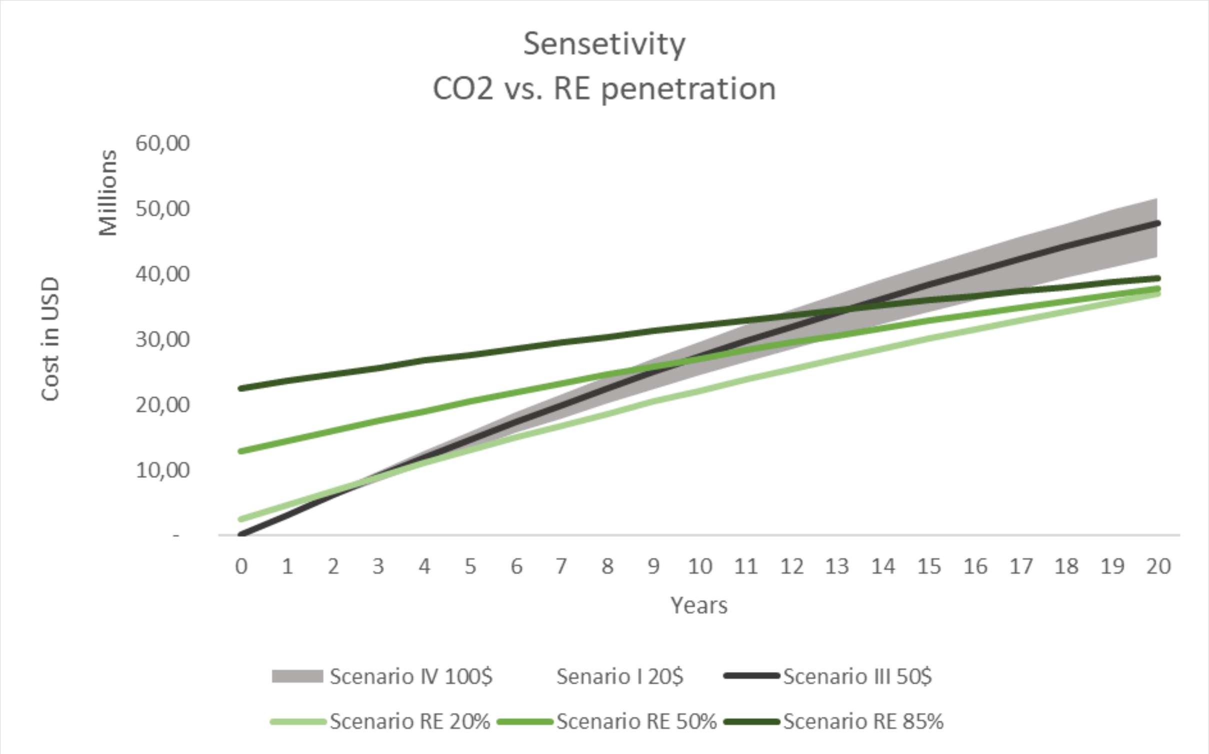

Figure 6. Sensitivity Analysis CO2 vs. Renewable Penetration

A.5. Conclusion

Several technologies were examined in the study and it was shown that they have already reached a cost competitive level, but further development can improve the technologies available and lower the price. In a cost benefit analysis, scenarios with different percentages of renewables levels with several mixtures of renewables sources were analysed, as well as the influence of CO2 pricing on the payback period of investment in renewables.

For a first integration of renewables a low-level penetration is very interesting. The electricity supply can become more secure, and the investment is relatively small and pays back in a short period. On the other hand a high penetration level with a local energy source, which gives energy independency from fossil fuels and reduces the risk of upstream energy security.
The transition process towards renewable energy can have several side effects on the environment. The reduction of fossil fuel usage can increase the local air quality around the generator side. All this leads to an increase in human wellbeing. On the other hand a few negative impacts can be associated with renewables. The technologies require more land use than diesel electricity generation. The land use can have an impact on wildlife, such as reducing grazing grounds, wind turbines can harm birds and hydro power fish migration. For further research on energy security in the Arctic it would be recommended to execute more detailed analysis on the VoLL. It can be assumed that the VoLL indicator in the Arctic differs from the VoLL in southern latitudes. The expectation is that the VoLL changes over the season and duration of the outage. The study shows that technology is available which can provide a secure and sustainable energy source
-051.

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Appendix B

Energy security in the Arctic: Policies and technologies for integration of renewable energy

B.1. Arctic energy systems

The Arctic can be defined by the Arctic Circle (66°33’), the tree line or the line of 10°C isotherm temperature in the summer [1]. This area faces harsh weather conditions with a long winter and short vegetation growth period. Around 4 million people inhabit the Arctic. Energy is an essential element for the survival of the population in the Arctic. Currently diesel dominates electricity generation in the Arctic. It can be seen that more than 80% of the communities exclusively depend on diesel. The diesel fuel has to be imported. The import can happen in several ways: on sea by barges during the summer time or by truck over frozen rivers during winter times. In just a few exceptional cases or in case of emergency, fuel has to be flown in. This makes the fuel transportation a critical point for electricity generation and adds a high cost to it. In addition to the aforementioned transportation issues of diesel, other negative issues are associated with the use of diesel. A global problem of burning diesel is the greenhouse gas emission with the well known effect on the climate. Besides greenhouse gases, black carbon is emitted, which has a special role in the Artic environment. Black carbon lowers the albedo effect locally. The albedo effect describes the reflection of solar radiation from a white surface, which protects the snow and ice from melting. The small black carbon particles absorb solar radiation and the snow and ice thaw faster. In the harsh Arctic conditions a secure and reliable energy supply is an essential need of the population. Over the last decades diesel has proven a very reliable energy source for electricity generation. Arctic diesel is a diesel with an additive, so that it can withstand temperatures up to -44°C and diesel engines need just a few minutes for a cold start (1 – 5 min) [2]. Furthermore, the engines can adjust the output to the demand of the electricity grid. The regulation of the voltage and frequency can be operated by the diesel generator. With the aforementioned advantages and disadvantages of diesel it can be seen that a movement towards a transition to renewable energy resources has started among Arctic communities. Some technologies have been adapted, but it is crucial to reinforce the momentum, which has started during the past peak in oil prices. The number of communities which are utilizing renewables is growing. Furthermore, on the political side a movement towards renewables has happened as result of the climate conferences (Paris, Marrakesh etc.). Alaska announced the aim to increase the share of renewables up to 50% by 2025 [3]. The Greenlandic aim is formulated quite vaguely: “By 2030, the goal is that the public energy supply must be, to the fullest extent possible, delivered from renewable energy sources” [4]. Canada has set a different aim that does not include the amount of renewables. Canada aims rather for greenhouse gas reductions of 30% compared to the 2005 level, which was 738 Mt CO2 equivalent [5]. The article is mainly based on a literature review which provides an overview of already existing research, and some information used in this article has been collected during visits for case studies in the Arctic region. The article aims to give an introductory overview on energy security in the Arctic. The focus lies on the political viewpoint, how can the energy security be improved by using technologies which are currently available on a mature level. First an overview on available technologies will be given, followed by a description of the energy policies of the different Arctic countries.

B.2. Technologies to harness renewable sources for electricity generation

Several renewable energy sources can be found in the Arctic. The following section focuses on sources which are widely separated over the Arctic and where the technology has reached maturity already. The renewable energy sources identified are; wind, solar, hydro, geothermal and current / tidal power. A closer look shows that geothermal power is primarily distributed around the ring of fire – Russian and Alaskan costal area at the Pacific

– and on Iceland. Current and tidal power is not mature yet and in Arctic regions as there can be a risk of ice and icebergs expected.

B.2.1. Hydropower

Hydropower is currently the energy source with the highest generation of electricity after diesel; the share accounts for 40% of electricity generation in the Arctic. The number of hydropower plants is relatively small, just a few relatively large hydro plants can be found in remote Arctic communities, mostly in larger communities. That is because the investment cost of hydropower plants is high and the cost per kilowatt increases with reduction of the power plant size [6]. On the other hand, hydropower plants have a long lifetime from 50 to 100 years and a low operation cost [6]. The energy output of such a dispatchable energy source is simple to regulate and the voltage and frequency is stable, which gives the electricity grid stability [6]. Depending on the type of Hydropower plant the environmental impact can be severe, in particular if a large storage lake is needed [7]. In cases where a bypass to a river is enough, the impact is less severe [7]. In any case a powerhouse is needed, which results in land use.

B.2.2. Wind Power

Wind power has good availability in the Arctic, with high potentials in coastal areas [8,9]. The general technology of wind turbines have to be adapted to the harsh Arctic conditions. Materials need to withstand temperatures below -40°C, which leads to significant changes in material properties [10]. Icing on the blades lead to significant problems which have to be addressed, for example with the use of black blades which are heated by solar radiation or heated blades [10,11]. The cold climate has a positive effect since it was observed by the US Department of Energy that wind turbines in cold regions have a 20% increase in maximum power output at around -37°C [12]. As in most construction related projects in the Arctic the cost is higher than in temperate areas. For a wind turbine it would be 2 - 3 times more expensive [13]. The generation cost of electricity is reduced to operation and maintenance after the payback period: no costs for fuel are needed [6]. The feasible lifetime of a wind turbine is around 20 years [14]. From a technical point of view, it can be even longer if the operation and maintenance costs are at an acceptable level. The environmental impact of wind turbines is related to the land use and the possible interference with wildlife, in particular bird migration [6,14].

B.2.3. Solar PV

Several photovoltaic solar systems are installed in the Arctic, mainly small scale for residential use or small businesses up to a 30 kW peak. The production of electricity is seasonal, according to the availability of sunlight. During the spring time it has been observed that the snow reflects the solar radiation and increases the electricity output of the solar cells [15]. Furthermore, the low temperatures increase the efficiency as well [15]. The solar cells have a lifetime of around 25 years [6]. The environmental impact of installing solar panels is very low. In most cases they are mounted on buildings, so that no land is used. In the case of solar farms, the land use has to be accounted for.

B.3. Current policies for renewable energy in the Arctic

The following section discusses the different political aims for energy among the Arctic countries, which have communities without any connection to a continental electricity grid.

This puts the focus on Alaska, Canada and Greenland. Furthermore, those strategies introduced to reach the aims are discussed as well.

B.3.1. Energy policy of Alaska

The Alaska State Legislator setup a Renewable Energy Fund (REF) in 2008 with annual contributions of 50 million USD [16]. The year 2008 was the peak year of oil prices [17]. First the fund was planned for five years, but in 2012 the fund was extended for ten more years [16]. The fund is managed by the Alaska Energy Authority, which is an independent, public corporation responsible for assisting energy projects development, operation and financing in the state of Alaska. The mission is to reduce the cost of energy and increase energy security. Other programs such as the 'Rural Power System Upgrades' programme helps rural communities with less than 2000 inhabitants to increase the efficiency of their generators [18]. Nearly 100 million USD has been leveraged since the introduction of that program in the year 2000 [18].

Since the introduction of the REF in Alaska over 280 grants for projects have been assessed and over 250 million USD have been allocated to projects. The fund helped 73 projects which are now in operation. With the executed projects it is possible to save a lot of diesel. The total financial savings from displaced diesel are annually over 70 million USD. In 2018 a number of the 56 projects supported by the REF have been under progress [18].

Another program very specific to remote communities is the Rural power System Upgrade (RPSU) programme, which has successfully completed 86 projects among small remote communities. The average increase of efficiency is around 15% but peaks sometimes even above 30%[18]. The increase in efficiency is due to a more efficient use of the diesel. For example, less diesel is used to provide the needed amount of energy – that would result in lower energy generation costs. Another example would be to recover heat from a generator and use it for heating purposes. This would not directly decrease the cost of generation, but the new product heat can be sold, which reduces the cost indirectly.

An observation shows that modern technology can be a problem in small remote communities. For example, clean and technically more complicated diesel engines according to the tier 4 standard are not very common. For such a technically complicated engine it is hard to find a skilled workforce in many remote places.

Alaska has a long experience with islanded microgrids. A lot of research and development has been done, on a scientific level e.g. at the Alaska Centre for Power and Energy or by private companies and utility companies. For this achievement, dedicated funds have been very important, from the state, region etc. Alaska is, with 25 – 30% renewables in the electricity mix, more than halfway towards its target of 50% renewables in 2025. It will be ambitious to achieve the remaining half in the next six years.

B.3.2. Energy policy of Canada

Canada's energy transition pathway is based on four pillars: first wasting less energy, second switching to clean power, third using more renewable fuels and fourth producing cleaner oil and gas [19]. These parameters are in alliance with the three general parameters for energy policy: affordability, reliability and cleanness [20]. A problem of introducing renewables are the high upfront costs on the investment side, which makes it important to have a strategy to support renewable projects. To increase the attractiveness of such projects the 'generation energy council report' recommends the introduction of capital cost depreciation, strategic initiatives and other tax treatments [19]. Moreover, existing funds and investment programs should be streamlined and the access to them should be extended [19]. To support the transition, subsidies for the use of fossil fuels in an inefficient way for electricity generation will phase out in 2025 [21].

The Canadian government's aim is to reduce the 2005 CO2 by 30% until the year 2030, which would entail a maximum CO2 emission of 500 Mt CO2. The long-term goal is even more ambitious with a reduction of 80% compared to 2005 by the year 2050. The CO2 emission of 2017 was 716 Mt CO2, a reduction of 2.9% compared to the 738 MT CO2 in 2005. In other terms it means that approximately 8% of the aimed reduction of 220 Mt CO2 was reached after 2 years. To reach this aim Canada has introduced several programmes to support renewable projects. The 'Energy Innovation Program' has allocated 49 million USD in over three years. The program is set up to support innovations for clean energy. The 'Canadian Renewable and Conservation Expenses' program is more consumer orientated, with the target group of industry. The program allows the write-off of equipment associated with producing clean energy with 30 – 50% per year. The common depreciation rate without the program would be 4 – 20 % per year for such equipment. The 'Green Infrastructure Program' has a sub-category, which focuses on 'Clean Energy for Rural and remote Communities'. The goal is to reduce dependency on diesel and establish local and clean sources such as wind, solar, biomass and hydropower.

Canada has just done a little step towards the aimed CO2 reduction in the first years. But it has to be considered that the supporting programs have to be first set up and introduced, and such projects take time before they show some effect. There are eleven more years to reach the aim. The funding options are relatively new, and they seem to be a mix aiming for research and development and for integration of renewables.

B.3.3. Energy policy of Greenland

The aim of the Greenlandic government is very vague, but the large communities are powered by hydropower. This makes the renewable portion of the total energy mix very strong with around 70% [22]. In 2016 the first solar test side was opened and in 2018 the first wind turbine was erected in Greenland. Private consumers have been much more open to solar power. Several small-scale solar systems can be found on residential buildings.

B.3.4. Comparison of energy policies among the Arctic countries

A comparison of the hydropower electricity generation in the different countries shows on a first look that Greenland produces more than 70% of its electricity by using renewables [22]. In Canada it is around 66% renewables [23](Natural Resources Canada, 2018). USA is far behind with 25 – 30% renewables, but these numbers are on a country level [24]. A breakdown on just remote areas draws a different picture. In Greenland all communities are remote, so nothing changes. But a look on Canadian remote communities shows that just 25% of all remote communities can supplement the diesel electricity generation with renewables. In Alaska 15% of all remote communities harvest a portion of the electricity from renewables. The lower use of renewables in remote places can be associated with the high investment cost for renewable power projects.

It can be seen that renewables are a viable option to support electricity generation and lower the carbon footprint of society. The introduction of renewables has a positive effect on electricity prices. It is among the Arctic communities that the highest electricity prices around the world can be found. For example, in Alaska prices can be 2 – 5 times higher compared to the lower 48.

B.4. Conclusion

At the current stage there is mature technology available to power entire Arctic communities by renewables like hydropower, or at least to supplement the electricity mix with renewable energy such as wind and solar. It is important to assess the local circumstances, which natural resources are available and which amount can be harnessed. Moreover, it has to be analysed if renewable energy can be harnessed in an economically viable way and cost-effective policies introduced to facilitate the transition. Alaska and Greenland have already implemented policies to support directly the use of renewable energy resources. Canada is however focusing directly on the reduction of greenhouse gas emissions, which will lead to an increase of low carbon technologies such as renewables. To reach these goal's several initiatives have been started by the governments, reaching from a country wide approach up to specific programs just for rural Arctic communities. Overall it can however be seen that the share of renewable energy in the Arctic is still very low.

Sustainable energy technologies are at a point of development where the integration in to Arctic electricity systems is feasible. The use of local energy sources can increase the energy security in communities and lower the cost of energy. For the small communities such projects are often very complicated to execute because of the high upfront investment cost. Since many sustainable systems are modular it is however possible for the communities to adjust the output in accordance to the demand, if the population growth or businesses require more energy. The policies that have already been introduced are helpful and the launched funding programmes are very important for supporting the implementation of renewable energy in the Arctic. However, more funding is needed to stimulate the transition, and smaller communities also need expert assistance for evaluating resource and technological potentials and with applying for funding.

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Appendix C

Dependence on Electricity Among the Inhabitants of the Rural Western Arctic

C.1. Introduction

The history of electricity generation in the Arctic dates back more than 100 years. One of the first hydro power plants in Alaska was built in the 1890s [1]. In many places in the Arctic the development of electricity infrastructure has taken place along with economic development. In the first days of the electrification of the Arctic the main economic drivers were trapping and mining. The Arctic Gold Rush, in particular, caused many people to move into the Arctic. It was followed by mining for other minerals and resources such as coal, diamonds, lead, zinc, etc., as well as recent on and off-shore oil projects [2-5]. Remoteness, lack of accessibility, and isolation are common characteristics of communities in the Far North, including Alaska, Yukon, Northwest Territories, Nunavut, Greenland, Svalbard, North-Western Russia, Ural, Siberia and the Russian Far East [6]. These communities have no connection to a regional or larger continental electricity grid. In the case of Finland and Sweden, however, such communities are fewer or non-existent. Over the past decades, remote communities have developed a strong reliance on diesel as a source of electricity generation [7,8]. This reliance has put the communities on a path of dependency, and the infrastructure has adapted to the needs of diesel [9]. Breaking out of the path of dependency requires a significant effort [10]. In the case of electricity supply, an economic and technological effort would be needed to shift the electricity generation setup. In the following, the relationship between Arctic inhabitants and electricity will be discussed. The focus is on two major issues. Firstly, the strong need for electricity by Arctic communities is analyzed. In the Arctic, electricity is not just a matter of productivity and entertainment, it is also essential for health and security due to the region's remoteness and harsh environmental conditions [11]. Secondly, the cost burden of electricity is considered, as high electricity costs create a considerable challenge in areas with existing high unemployment and poverty [12,13]. Under these conditions high cost of electricity can lead to increased social and economic problems. This study will discuss the question of the potential benefits in terms of reduced social costs of breaking the path of electricity dependency.

C.2. Methodology

The basis of the analysis of the value of lost load (VoLL) comes from the literature, which describes the situation in North America and Europe [14-16]. In North America and Europe, the main difference in VoLL is related to the difference in economic productivity. Some studies have shown high values for VoLL of up to 250 US$/kWh (in the US and New Zealand) [15]. In other places the values can be much lower, depending on the economic power and type of economy. In the present research two scenarios are presented, firstly a blackout during the summer, and secondly a blackout during the winter. The winter scenario is unique in the Arctic due to the harsh and very cold climatic conditions during the winter [17]. In this study, dealing with the burden of electricity costs in Arctic areas, we use the database from our previous study on energy consumption and production patterns in the Arctic [18]. Some additional data has been gathered to carry out the present study. From the previous study the electricity consumption in the communities under discussion was known, but for the current research it was necessary to extend the data collection with data on the income structure in those communities. This information was publicly available from the national statistical offices and the national census. Several analyses on the burden of electricity cost in the Arctic were conducted using data collected for this study.

C.3. Results

Economies of communities in the Arctic differ from those of the Western Hemisphere. Today subsistence continues to make an important contribution to social and economic life in northern communities, due to culture and tradition [19]. Local economies are a combination of market based and non-market based traditional economies [5,19-21]. Since the middle of the last century modern technology, such as snow machines, rifles and the housing situation with home appliance, has changed the economy [19,22]. To acquire such technologies money was needed and both types of economies have merged to form a mixed economy. It can be observed that the catch is shared among the members of the community, and hunting is a community effort [19,21]. The informal part of the economy is often neglected in income databases for the region, and therefore we attempt to estimate the value of the informal economy in this study.

C.3.1. Simulation of a Blackout

The value of lost load (VoLL) describes the monetary impact associated with an interruption in electricity supply [15,16]. The value of lost load (VoLL) takes into account the loss in economic production as well as losses in social life. VoLL can vary significantly in different areas. For example, the study of Anderson [16] calculates a VoLL of 100 US$/kWh for New York south of 42nd Street after Hurricane Sandy in 2012. This high value is due to the high financial power in that particular area. Studies for other areas show much lower values, e.g. in Austria where VoLL was estimated to be approximately 10 US$/kWh [14]. In the Arctic it can be expected that the VoLL is relatively low due to the small sizes of local and regional economies. However, a blackout during the harsh winter months could lead to a breakdown in the utility infrastructure—bursting freshwater pipes and district heating pipes. This very close relation between the inhabitants and energy will be further studied in the following simulation. To show the special Arctic situation, two scenarios have been constructed: firstly, a blackout during summer times, which can be seen as a base case that considers economic and private losses; the second scenario, more specific to the Arctic—a blackout under the harsh conditions of Arctic winter, which still considers economic and private losses, but also includes the losses from damages to the utility infrastructure. The usual implications of a blackout are represented in Figure 1. The first implication is for the private life, which represents the inconvenience in recreational routines, such as watching TV, listening to music, browsing the internet or socializing with other people, which can be disrupted. Taggging this with a monetary value is very complicated, because everyone values their recreational activities differently. Some things, such as meeting friends, are nice to have, others are a necessity, for example housekeeping. The private part of VoLL must also include the damage to food from non-working fridges and data losses on computers due to the blackout. Some literature estimates a value of 10 US$/kWh for private losses [14,15]. For the Arctic a similar, although perhaps slightly lower value can be assumed due to a reduced offer of activities. As already mentioned, the economic loss is very dependent on the economic activities. In the Arctic different types of communities can be seen, with different kinds of sustenance. This paper takes Kotzebue in Alaska as an example to estimate the VoLL. The VoLL is calculated as shown in formula (1).

$$1)\quad VoLL = \frac{GRP_{per\ Capita} * Population}{Comercial\ electricity\ sales}$$

2) $VoLL = \frac{59.420 * 3.154}{10.407.000}$

3) $VoLL = 18{,}01\ US\$/kWh$

The Gross Regional Product (GRP) per capita in Alaska was 59.420 US$ in 2018 [23]. This value does not capture the informal economy, and therefore provides a biased estimate. People in the Arctic participate in both informal and formal economies, of which only the reported part (the formal economy) is captured in official statistics [24].

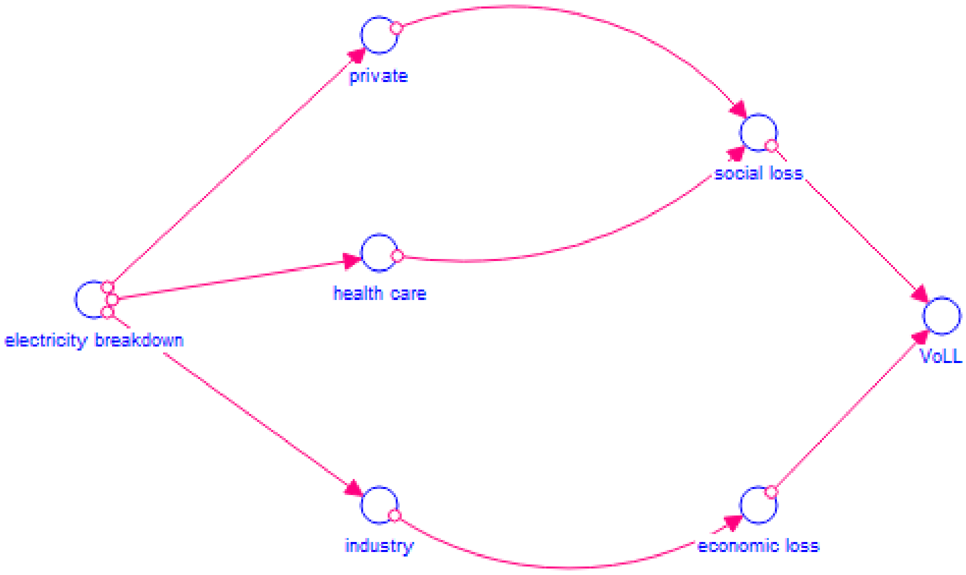

Figure 1. shows how an electricity breakdown leads to the VoLL under normal circumstances

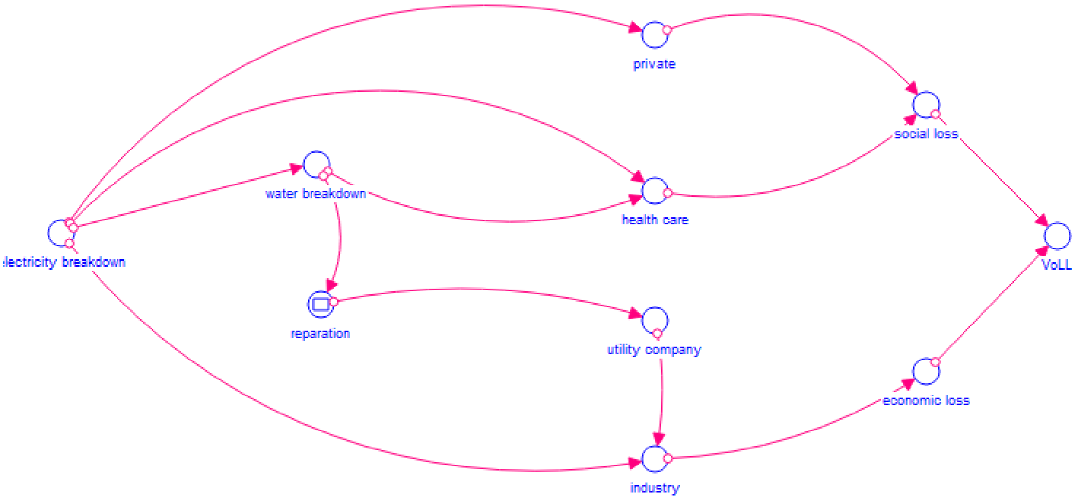

Figure 2. shows how an electricity breakdown leads to the VoLL during the winter-times

The population of Kotzebue was 3.154 in 2017 [25]. The commercial electricity consumption of Kotzebue was 10.407 MWh in 2013 [25]. All this leads to an approximation of the VoLL of 18 US$/kWh in Kotzebue. However, since the GRP per capita used in the calculations is the average for Alaska, this value is an approximation. For a more meaningful VoLL it would be necessary to examine the economy of Kotzebue in more detail. It can be expected that the basic healthcare system continues to be provided, with the help of back-up generators in the hospital. Subsistence has a significant social and cultural importance among Inuit communities. A closer look at the technologies used for subsistence activities shows that they are relatively independent from electricity, e.g. snow-machines, all-terrain vehicles, motorboats and rifles [22], which suggests more reliance on fuel than on electricity. Therefore, the informal segment of the mixed economy is not included in the following. During winter the harsh Arctic climate creates an additional impact on the utility infrastructure. The absence of electricity can cascade down to the fresh water supply and, if available, to the district heating system, as represented in Figure 2. The missing heating and electricity can have a negative impact on people in the cold climate and may reduce the health safety [11]. Private and health care losses may lead to a social loss, the size of which is difficult to determine since it is partly on the economical side and social side and can be also influenced directly and indirectly by the interruption in electricity delivery [14,15]. Losses due to health care and social challenges lead to an expected higher VoLL value in winter than under normal conditions in the presented study. The literature has estimated high values for the private VoLL to approximate 40 US$/kWh in Tol’s research [15]. In the winter an additional reparation cost for utility infrastructure must be added to the 18 US$/kWh. The utility reparation cost cannot be expressed in terms of dollar per kWh. Furthermore, the reparation of utilities such as water and district heating can prolong the loss in the industrial sector. Fisheries is one of the main industries in the Arctic, and water is needed for fish processing [26,27].

C.3.2. Burden of Electricity Cost for the Inhabitants of the Western Arctic

High rates of unemployment and poverty present significant challenges in many parts of the Arctic, and even more so in many indigenous communities [12,13]. The following shows the impact of electricity costs on the life in northern communities. As shown in Figure 3, the cost burden in rural Alaska is significant, with up to 45% of the net income spent on electricity. Therefore, it is assumed that the average consumption per household is 572 kWh per month in 2018, with the average household accommodating 2,74 people [28,29].

Table 1. comparison of the main properties indigenous and non-indigenous communities. The data set is the same as used in Figure 3.

	Non-Indigenous			Indigenous		
	min	max	average	min	max	average
Population	16	2.768	526	7	6.329	501
el. Price (US¢/kWh)	20	116	57	8	181	62
Income per capita US$	8.761	31.747	19.086	5.469	28.941	13.138

Table 1 shows the main properties of the comparison, with 164 samples collected in Alaska, of which 143 communities were recognized as indigenous ones, and the remaining 21 not recognized as indigenous communities, and therefore categorized as non-indigenous ones. A more detailed look at the situation shows different patterns for communities, which are recognized by the state as indigenous entities and are eligible by the state to receive services from the US Bureau of Indian Affairs [30]. In terms of community size and electricity prices it can be seen that the range for indigenous communities is larger, but, as seen in Figure 4, the average values of indigenous and non-indigenous communities are close together. In terms of monetary income per capita, for the average non-indigenous communities it is considerably higher, i.e. 13.138 US$ on average in indigenous communities compared to 19.086 US$ in non-indigenous ones. The studies of Wenzel [22] and BurnSilver [21] show that the catch per capita is 120-360 kg per annum for several villages in the Alaskan and Canadian Arctic. This would add approximately 1.200 - 3.600 US$ per year to the per capita income in natural goods, with a price of 10 US$ per kg of harvested goods accordingly [22]. This would increase the income of indigenous people in the Arctic. For the non-indigenous villages, the cost of electricity is 11% of their income ad maximum. For the indigenous communities the maximum is at 30%, which is nearly three times as high as for non-indigenous communities

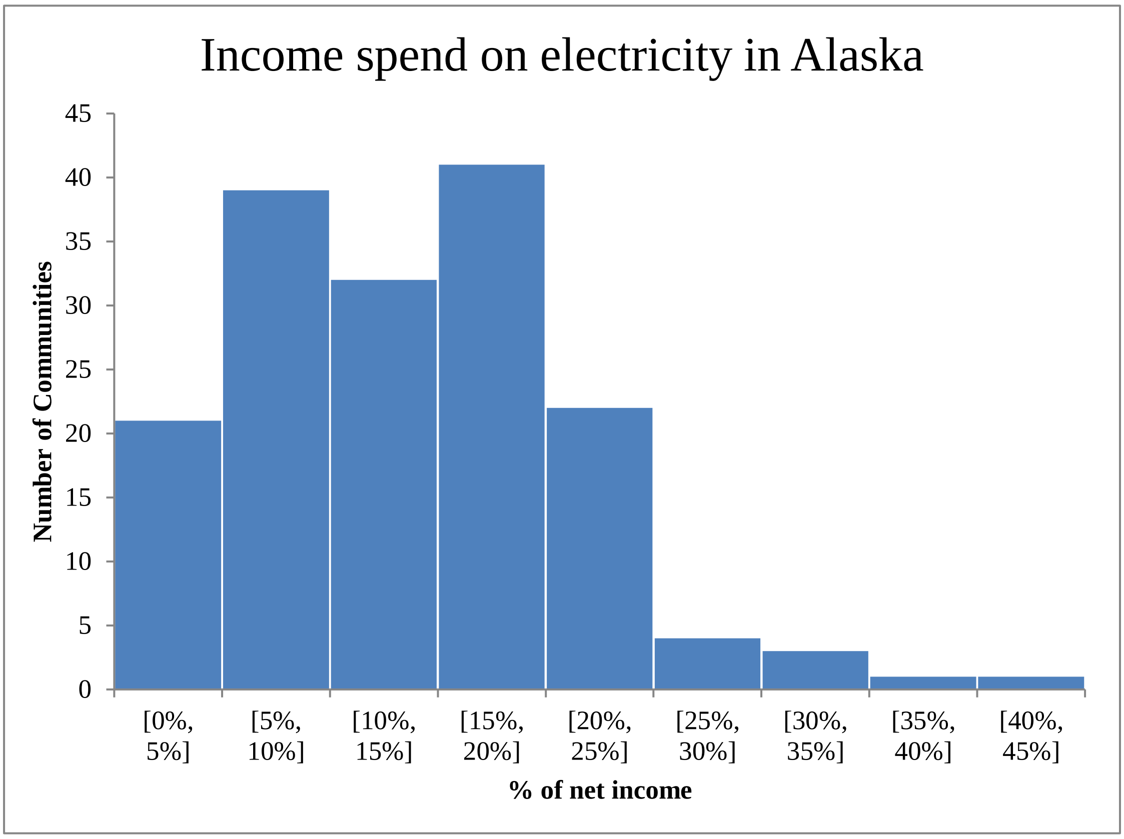

Figure 3. shows the average proportion of net income, households in Alaska spent on electricity. The graph is based on electricity prices from [25], average Alaska energy consumption from [29] and the average income in the communitiesis extracted from [28].

The different lifestyles of indigenous and non-indigenous communities may, however, affect the electricity consumption. Among indigenous communities, where subsistence is customary and makes up an important part of material wellbeing of households, the demand for electricity may be lower. We therefore attempt to account for this effect as well and the collected data on electricity sales for residential purpose. Figure 5 shows that the burden of electricity costs for indigenous communities is much lower than in the previous, more generalized, analysis, but it is still high. The big difference between the previous graphs (Figure 3) leads to the conclusion that electricity consumption in the connected part of Alaska must be higher, to lift the average electricity bill per household up to 572 kWh per month. The previous steps have analyzed the burden of electricity in remote Alaska within the context of the formal economy. At the next step the informal economy is introduced to account more accurately for the burden of electricity costs in the case of a mixed economy setting (see Figure 6). Therefore, two scenarios have been established: a low subsistence scenario, which adds 1.200 US$ to the income per capita in indigenous communities; and a case of high subsistence, which adds 3.600 US$ to the indigenous income per capita. The origin of the values is explained earlier in this section. Results for the Canadian Arctic can be expected to be similar to the US Arctic, since the lifestyle is similar and both regions have high rates of poverty and unemployment.

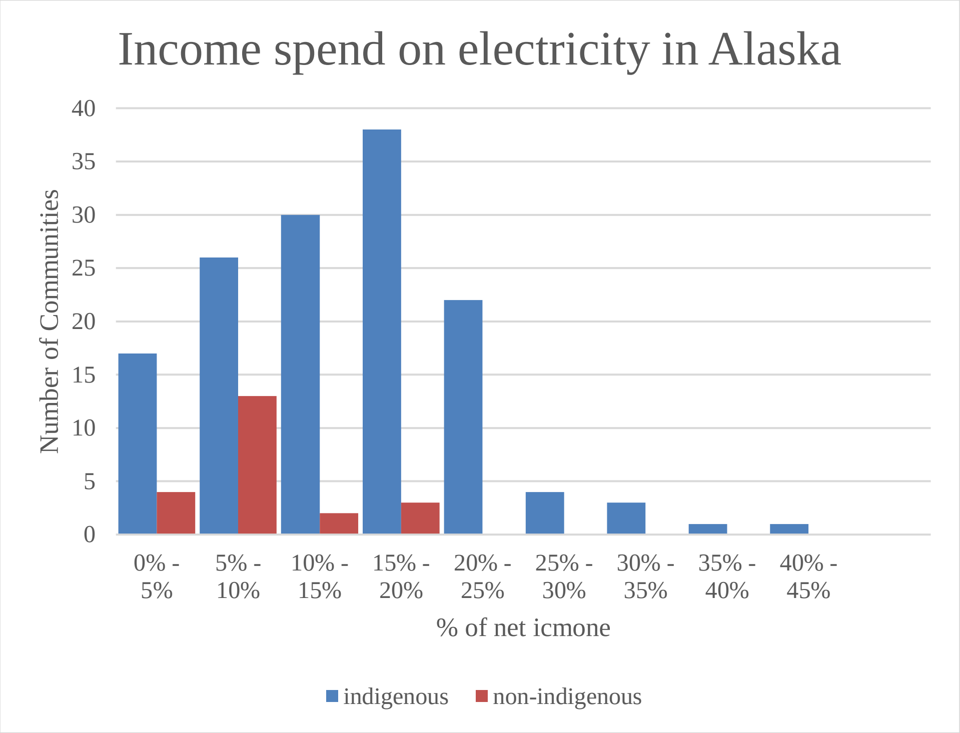

Figure 4. Comparison of net income spent in rural Alaska on electricity by indigenous and non-indigenous based communities with the Alaska average electricity consumption. The data set is the same as in Figure 3 but the communities have been grouped into indigenous and non-indigenous communities in according to [30].

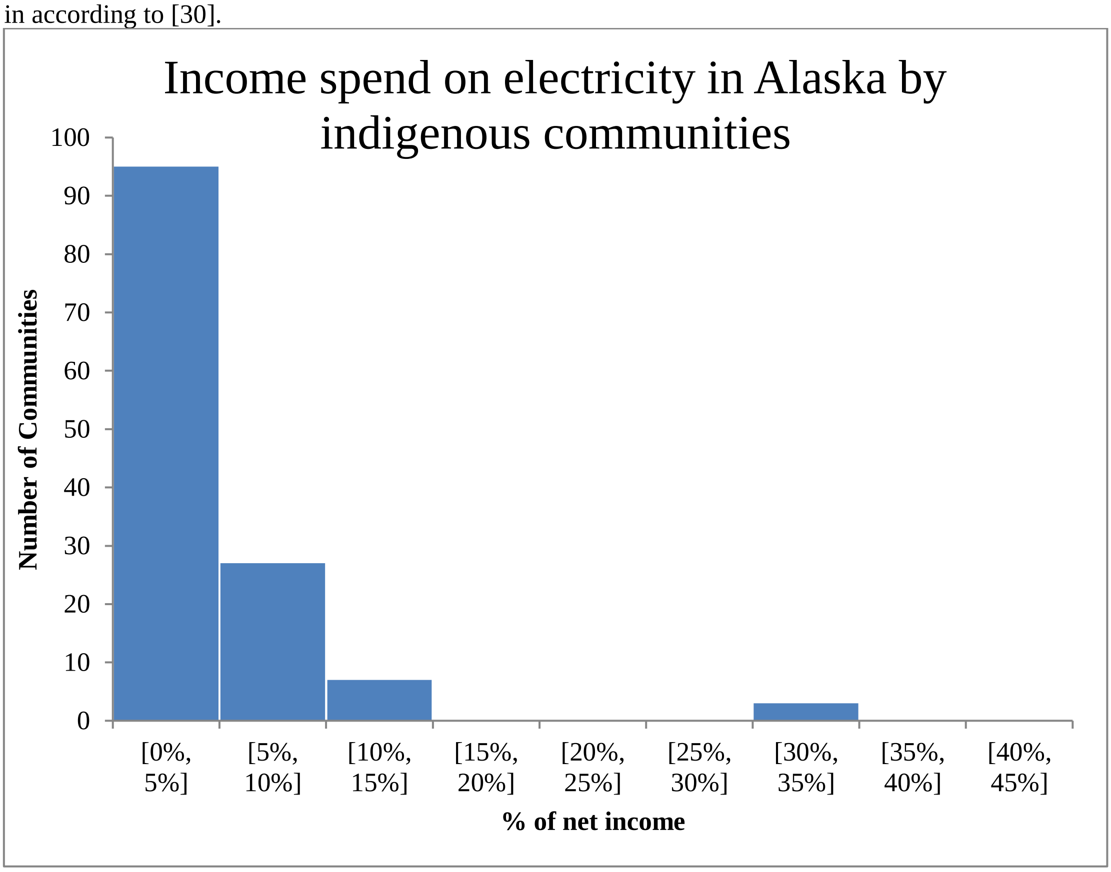

Figure 5 shows the net income spent on electricity in relation to the local electricity consumption. In Figure 3 and 4 the average consumption of Alaska was the base, Figure 5 took the residential electricity sold and divided it by the population of the community.

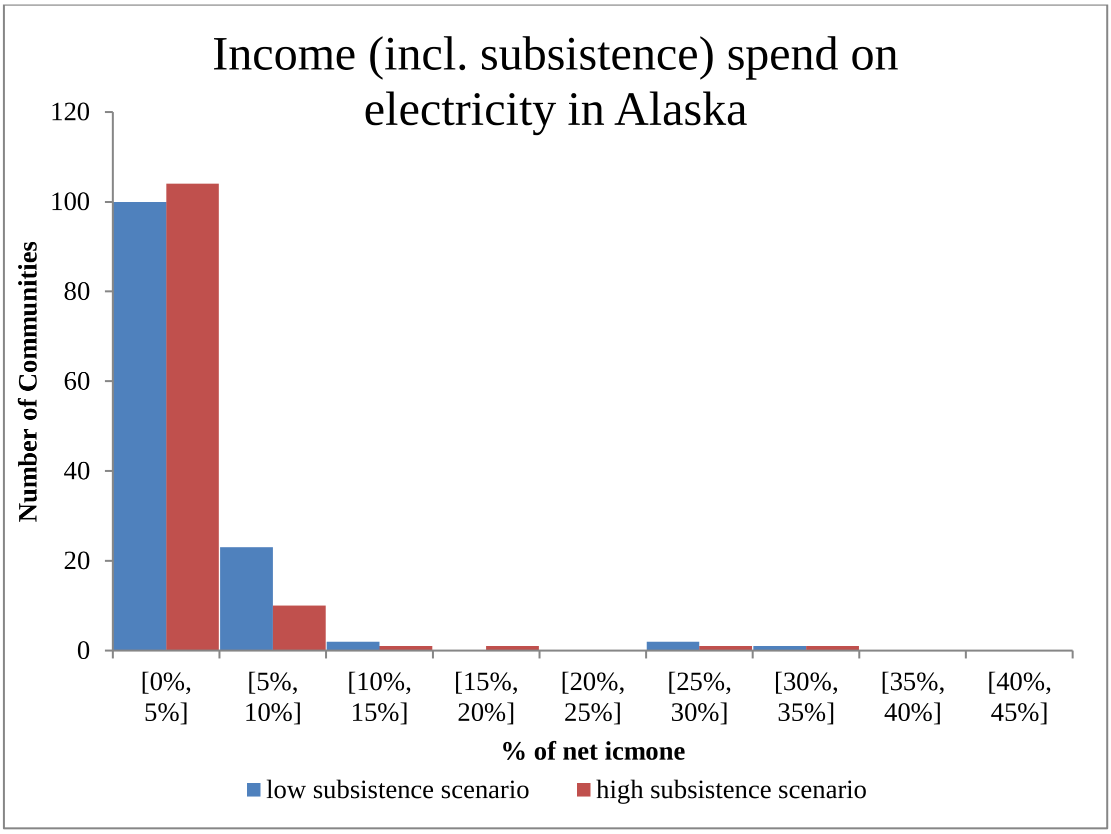

Figure 6. shows the net income including subsistence spent on electricity in relation to the local electricity consumption (low subsistence scenario net income + 1.200 US$ for indigenous, high subsistence scenario net income + 3.600 US$ for indigenous)

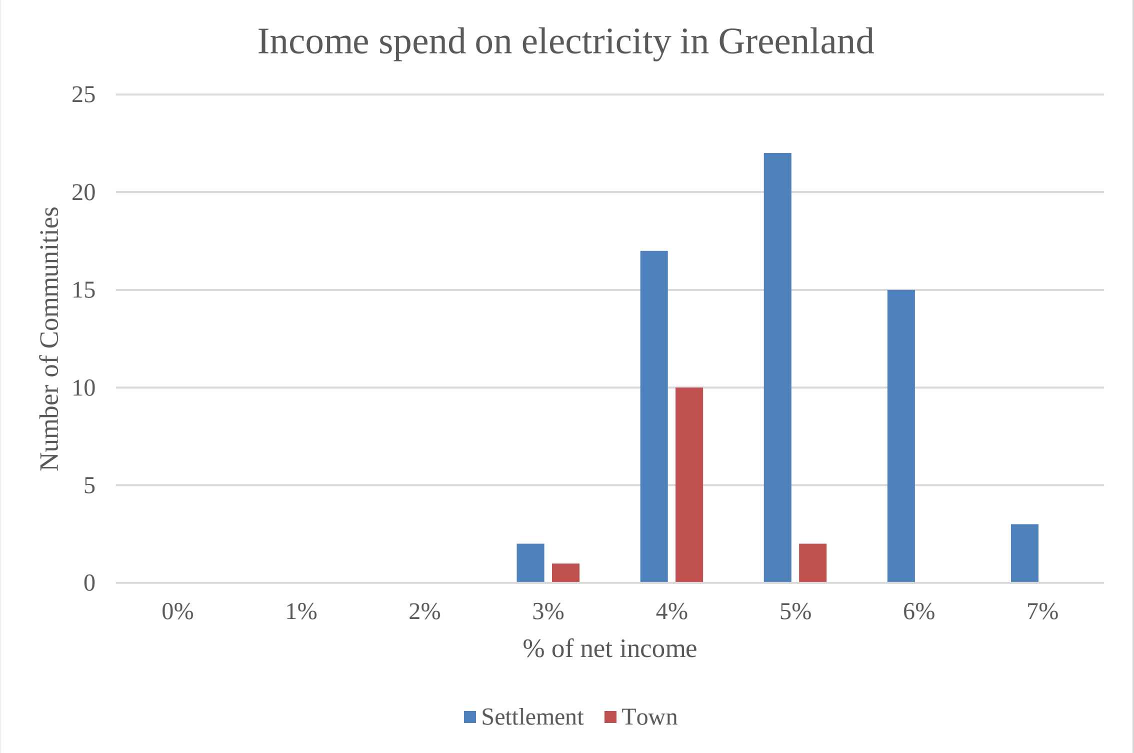

Figure 7. shows the net income spent on electricity in Greenland, distinguished between towns (more than 1.000 inhabitants) and settlements (less than 1.000 inhabitants)

The main difference in this sense is that in the Canadian Arctic the cost of electricity is slightly lower that in the US Arctic. A look at Greenland shows a completely different picture. The highest percentage of net income spent on electricity is seven percent. As shown in Figure 7, the difference between towns and settlements is not big (in Greenland the distinction between town and settlement is defined by a population of 1.000 inhabitants). In January 2018, the Greenlandic government launched a new policy of uniform prices for electricity and water [31]. Since then, all communities in Greenland pay the same price for electricity, which has resulted in huge savings for remote places. For example, the government predictions show cost savings of 51% for water and electricity for a family (two parents and two children) in Sarfannguit [32].

The results of the analysis of the electricity prices in remote Arctic communities suggest that high electricity prices have an impact on the residential market and present a burden for the local economy. High electricity prices may result in lower economic capacity, which will lead to lower income. This vicious cycle presents a big challenge for Arctic communities. A solution to break the vicious cycle could be renewable energy. For several communities, where renewable energy sources have been introduced, lower electricity prices have been achieved over a mid-term time horizon in some Alaskan communities. In Greenlandic communities an electricity price difference was visible before the unified electricity price was introduced in 2018 [33,34]. Given the availability of renewable energy resources, renewable energy has been shown to have the potential for providing affordable electricity, as well as jobs [35]. The main renewable energy technologies found in the Arctic are hydro power, wind power and photovoltaic [8,36,37]. Even if renewable energy production does not create many new local jobs, a lower long-term price for electricity may help to improve the local economy. Lower electricity prices, available through the use of renewable energy in remote Arctic communities, can contribute to achieving the UN sustainable development goal 7, ‘affordable and clean energy’ [38]. Moreover, the introduction of renewable energy can contribute to the UN sustainable development goal 1, ‘no poverty’ [38]. As shown in the previous sections, it is important to take social aspects into account for the design of an energy transition strategy. The summer and winter cases of the VoLL show that the inhabitants of the Arctic have a critical need for a secure electricity supply, especially during the cold winter. On the other hand, high electricity prices create a considerable cost burden in the Arctic. The size of the cost burden underscores the importance of having in place a transition process towards local renewable energy with lower electricity prices. A previous study has pinpointed that the needed technology is available and proven under the harsh Arctic conditions, and that renewables can help to reduce the cost burden of electricity and improve energy security [39]

C.4. Conclusion

This paper emphasizes the social importance of going further in the direction of a sustainable energy transition in the remote Arctic. Electricity plays a crucial role in the Arctic for the survival and general wellbeing of population. Therefore, it is important to ensure a reliable and constant electricity supply at an affordable price. In some parts of the Arctic initiatives have been launched to overcome this problem, but there is still a huge discrepancy between small and large communities in many regions, as well as indigenous and non-indigenous communities. It is important to lower the overall level of the percentage spent on electricity and close the income gaps between communities of different sizes and between indigenous and non-indigenous cost burdens. In the accomplishment of these tasks renewables can play a key role. However, in areas with a weak economy, such a transition has to be carried out in a sensitive and inclusive way. It is therefore important to find optimal solutions to the transition from fossil fuel towards renewable energy sources. Hence, further studies are needed on the transition process.

C.5. References

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