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

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Abstract: This paper examines the various pathways toward energy transition available to remote Arctic communities. Inhabitants of Arctic communities often face significant cost burdens due to high energy prices. Electricity costs are particularly high, due in part to the predominant use of diesel for electricity generation in over 80% of remote Arctic communities. This study examines the different approaches for integrating renewable energy sources, with a focus on the different strategies that might be implemented to finance the energy transition toward greater use of such renewable sources. The high costs associated with project realization in the remote Arctic present special challenges. This study uses a system dynamics model to evaluate the various financing tools available to facilitate the energy transition. The model results indicate that the integration of renewable energy sources has the potential to yield long-term electricity cost savings for the remote Arctic communities in question.

Keywords: Arctic energy; sustainable energy; energy transition; system dynamics; energy financing

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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 by 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 the use of 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 resulting in high transportation costs. These high transportation costs in turn result in high electricity prices, perhaps as high as USD 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 [5–7]. However, the energy transition process is likely to be exceptionally challenging because of the harsh climate and remoteness of the area, 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 intensive [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 those 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. The study also 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 investigated in this study. Regarding the technical aspects of the energy transition, the following questions, which have been elaborated in preliminary studies [1,12], are crucial for the execution of this study. Which technology options are available for the transition process, and can they be used or adapted to the specific location [1]? The research in [1] concludes that hydropower is well proven, with a high potential for electricity cost savings. Moreover, wind and photovoltaic (PV) power have been proven toto be effective 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]? The work presented in [12] concludes that locally generated renewables can help to increase mid-term energy security by increasing the independence from fossil fuels. On the other hand, 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 have 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 combination with the setup of the system dynamics model.

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 a 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 the areas of project and change management to analyze the impact of delays and interruptions, which may be expected in the renewable energy integration process. Advanced 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 [17,18]. 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 behaviors 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 use in the analysis of the transition process in remote Arctic communities. SD has not been used previously to analyze the transition processes of island microgrids. Nevertheless, but it has exhibited exceptional potential for other transition processes [20–25] 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 of energy, environment, infrastructure, building, and residential consumers. The interviews were conducted in Svalbard, Nuuk, Maniitsoq, Napasoq, Anchorage, Kotzebue, and Noatak in the period from November 2018 until 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, as well as complex issues [29–31]. 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 the use of 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 following section.

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 with 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 using the following.

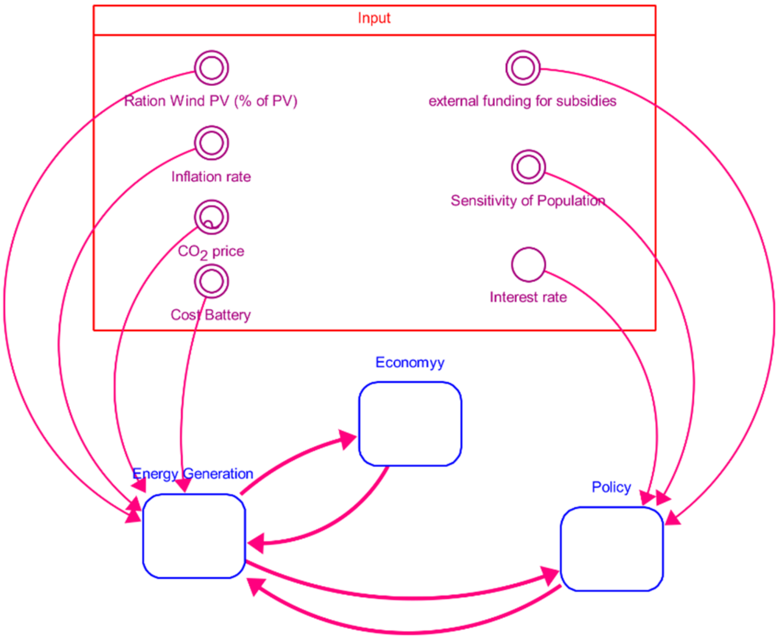

Figure 1. Sub-system model showing how the three sub-systems—energy generation, economy, and policy—interact with one another. The input box represents variables assumed to be changed by the user to create different scenarios.

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 "climate change" variable, 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 "external funding for subsidies" variable.

3.2. Assumptions and Key Variables

The model represents a fictive Arctic community with a population of 3150 inhabitants (This approximately represents the average size of the communities in the field study: Longyearbyen, Maniitsoq and Kotzebue). 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 shown in Table 1 Changes in the variable over time have been implemented, based on predictions from the literature review and shown in Table 1. Regarding renewable energy 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.

The maximum penetration level of renewables is assumed to be 80%. 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 renewable penetration of 80% in the energy mix was selected, corresponding to the suggestions in the literature [37]. The literature reviews have previously 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 renewable penetration levels 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 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, such as energy generation equipment and energy storage equipment, to fulfill the policymaker's targets for the renewables' installed capacity. It also represents investments made with the aim of replacing the 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 a 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 provided by the user. 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	USD/t	[38]
Battery cost	fixed	3640	USD/kW	[39]
External funding for subsidies	variable	25,000	USD	user
Inflation rate	fixed	2	%	[40]
Interest rate	fixed	5	%	[41]
Max RE penetration	fixed	80	%	[37]
Wind Ration PV (% of PV)	fixed	40	%	user
Unemployment rate	initial	12.2	%	[42]
Money generated by jobs	initial	2500	USD/month	[4]
Population	initial	3150	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	USD/kW	[43]
Diesel fuel consumption	fixed	0.25	liter/kWh	field visit
Fuel price	initial	0.85	USD/liter	[44]
PV installation costs	fixed	3000	USDkW	[33,45]
Wind installation costs	fixed	2500	USD/kW	[9,46]
Diesel O&M costs	fixed	0.2	USD/kWh	[47]
PV O&M costs	fixed	9.1	USD/kW	[48,49]
Wind O&M costs	fixed	3	%	[50]
Climate change	variable	0–2	°C	[32]

3.3. Sub-Systems

The model consists of 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 sub-system focuses on the different energy generation technologies that 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 section, the cost of energy generation, installation, 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 data regarding the 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 regards to technology and the generation of electricity. Therefore, the model calculates how much capacity must be created and estimates the installation costs and the cost of generating energy.

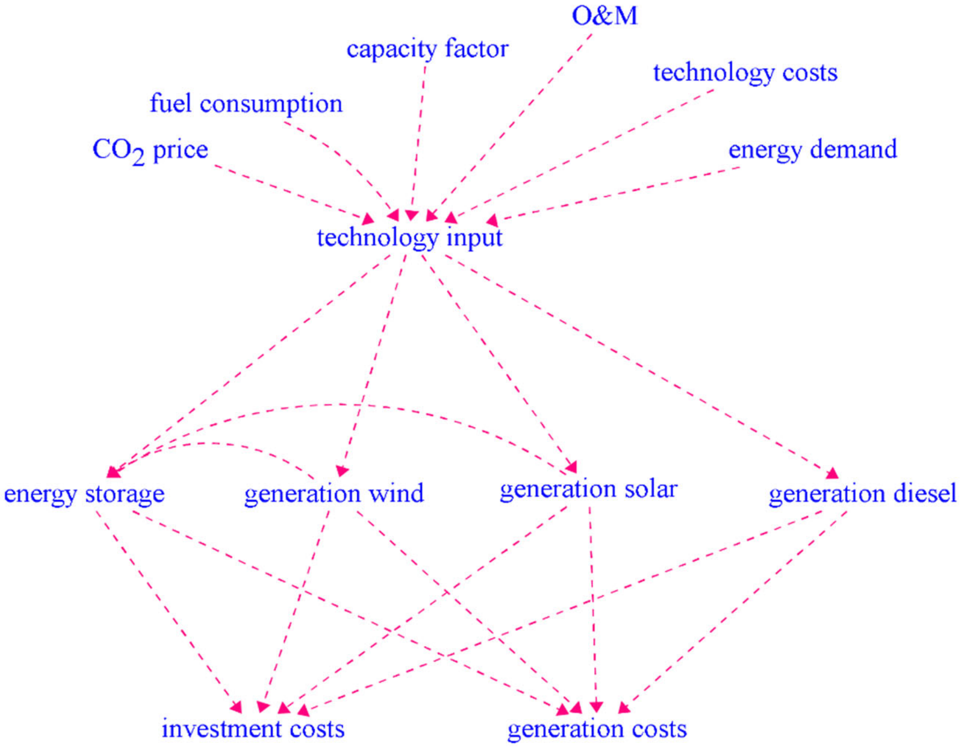

Figure 2. The energy generation sub-system compiles the technology input for the economic sub-system. It is a straightforward sub-system that arranges the technology portion in accordance with the external input. For the calculation, all input variables and the given energy demand per technology are 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 sub-system may be divided into a general microeconomics model and the energy provider's microeconomic behavior. The general economics portion 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 portion analyzes the electricity sales price in loop B1, shown 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. Thus, the model 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 certain limit. The nature of the model is to increase the share of renewables, covering 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 this specific case, the model aims to harmonize the environmental aspect by increasing the use of renewables, the social aspect by offering the lowest possible electricity prices, and the economic aspect by giving the utility company liquidity to operate.

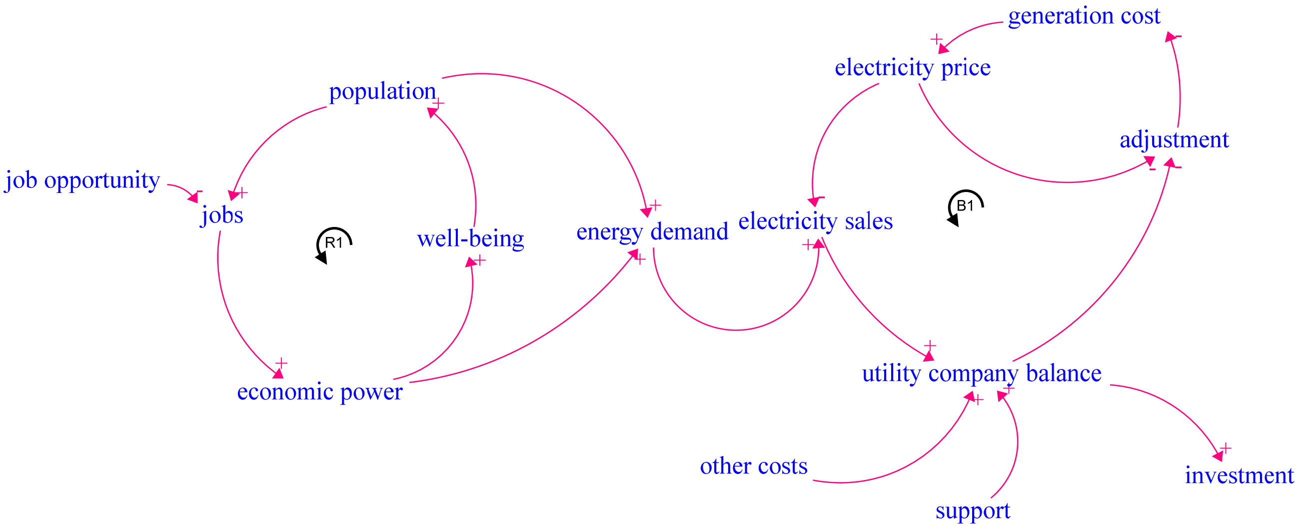

Figure 3. The economy sub-system has two loops: one loop represents the local economy, and the other loop represents the utility company and its pricing strategy. The key variables are energy demand, which provides sales feedback, and the energy generation sub-model. The main input is the generation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

Policy: This sub-system 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, possibly causing renewable 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, resulting from delays in the decision-making process. The second main feature focuses on subsidies, which may be financed by a CO_2 tax, external funding, or a 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.

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 subject to 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 for 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, 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.

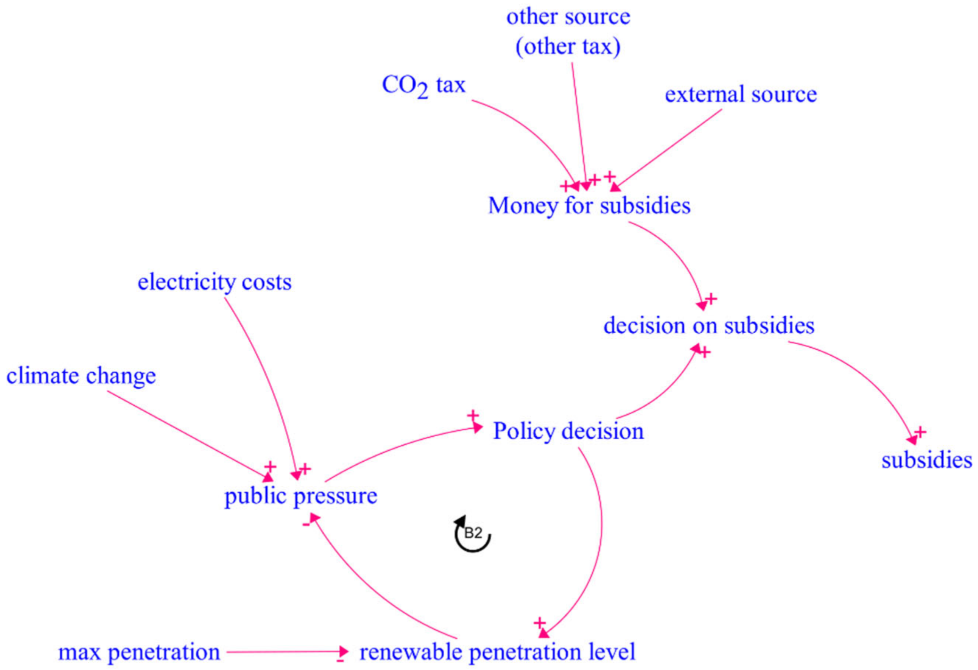

Figure 4. The main function is loop B2, which represents the integration of renewables. Another feature is the subsidy mechanisms in the sub-system, which will be used as an external input for the economic sub-model.

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.

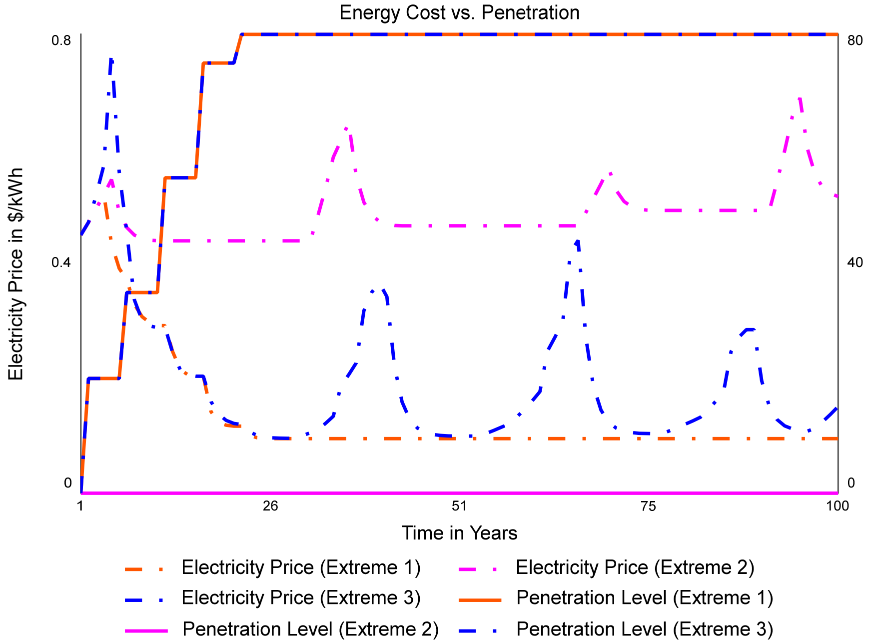

Figure 5. Renewable penetration and electricity price response under three extreme conditions: Extreme 1: high public pressure and unlimited financial support; Extreme 2: negative public pressure and unlimited financial support; Extreme 3: high public pressure and no financial support.

4. 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 using 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 Results 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 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

4.1. 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.

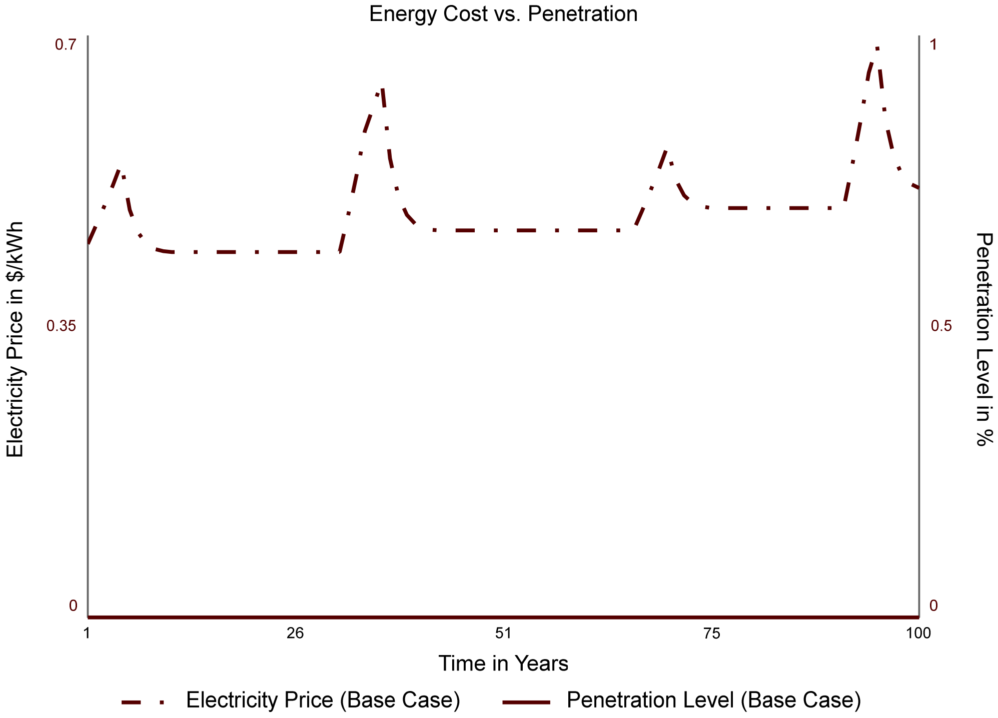

Figure 6. The energy price for the business-as-usual case. The first peak occurs because the simulation starts with no money in the utility company's bank account, and some funds are needed for repair and re-investment. The three subsequent peaks are the result of diesel engine replacement. The penetration 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. The 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, along with 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 for maintaining these generators [54].

Figure 8 illustrates the investments required for the replacement of 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 of new diesel generators for future savings. As Figure 7 illustrates, loans are required to cover the investment at time steps 30 and 90.

Figure 8 illustrates the investments required for the replacement of 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 of new diesel generators for future savings. As Figure 7 illustrates, loans are required to cover the investment at time steps 30 and 90.

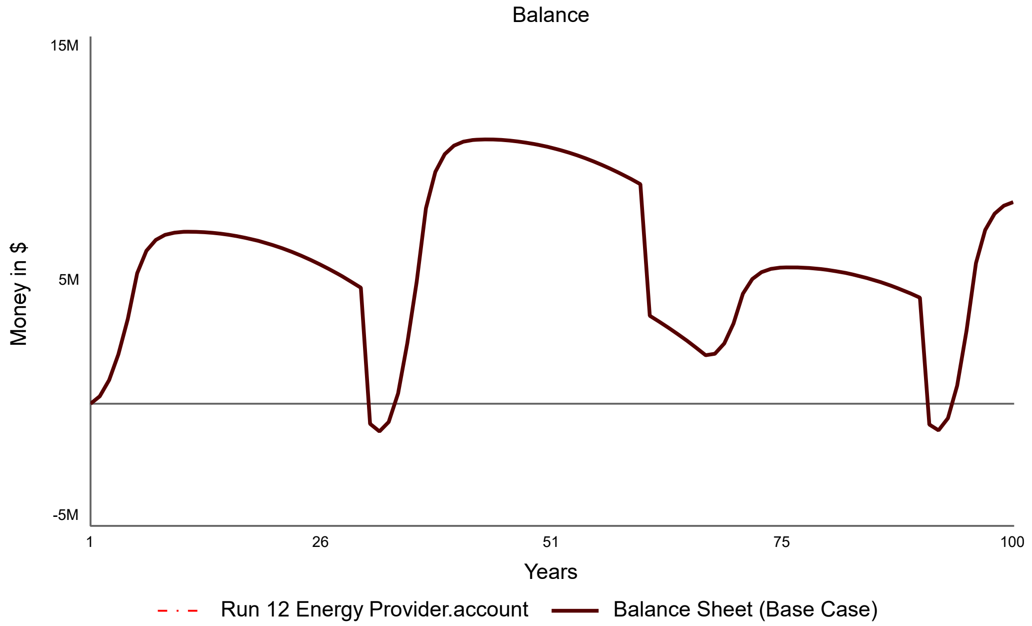

Figure 7. The balance of the utility company account in USD, which shows the three troughs resulting from the investment in new diesel generators. Each plateau's slight decline is the result of inflation.

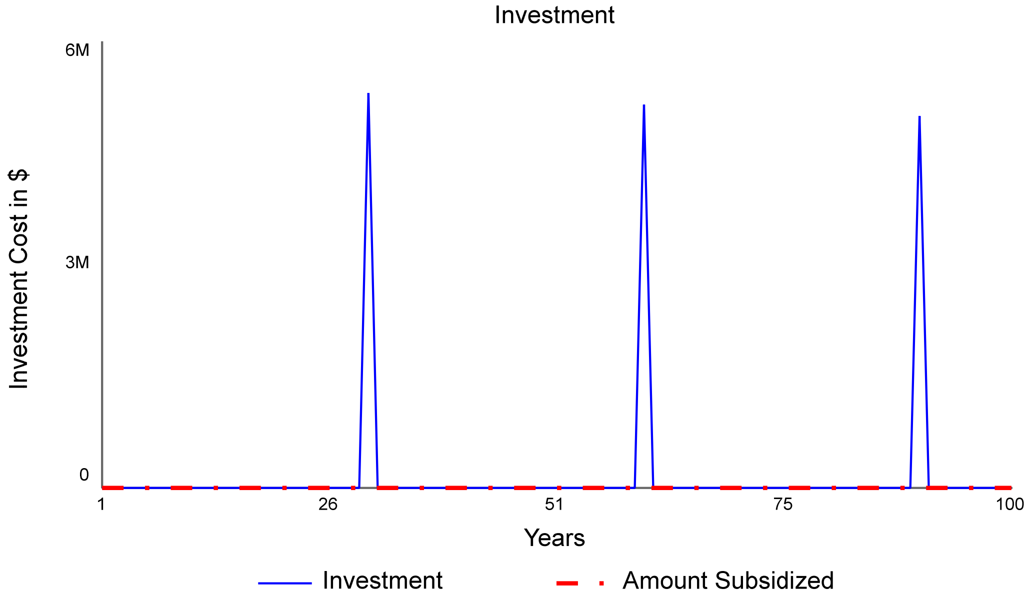

Figure 8. No subsidies for the investment is indicated by the red line. Only three investments are made for new diesel generators, indicated by the blue line.

Figure 9 shows different integration cases of renewables. The solid lines represent renewable 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 with slightly lower electricity prices. Cases 1 and 3, which show slower renewable integration rates, show slightly higher electricity costs, on average, than cases 2 and 4. Case 3 has a lower electricity price throughout the entire simulated period.

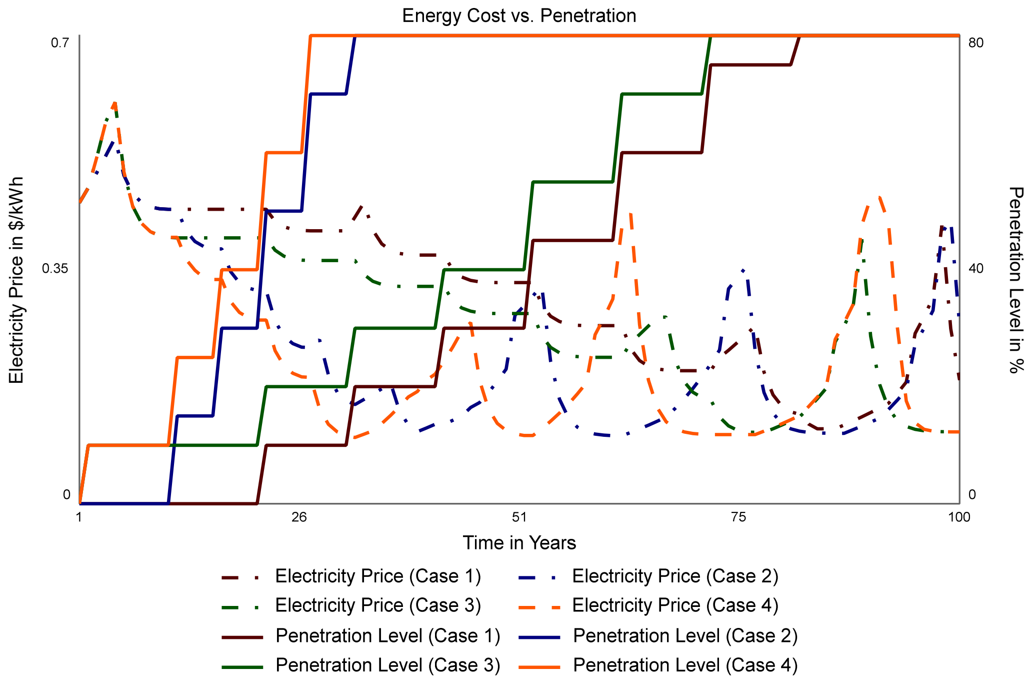

Figure 9. Energy costs vs. renewable penetration levels. The penetration level stems from public pressure and policy, and the electricity price is the result. The solid lines represent renewable penetration levels, and the dashed lines represent the electricity prices.

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].

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 inherent in 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 correlate 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.

4.2. Scenario 2: CO_2 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.

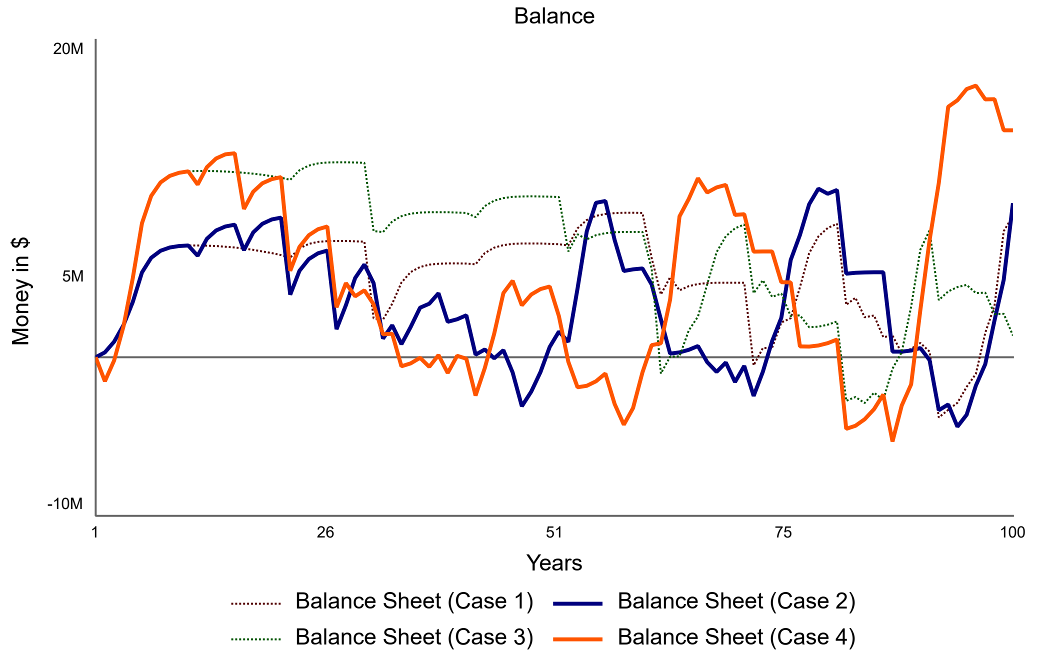

Figure 10. Balance of the utilities account. The solid lines represent the cases with a fast energy transition. The dotted lines represent the slow transition cases.

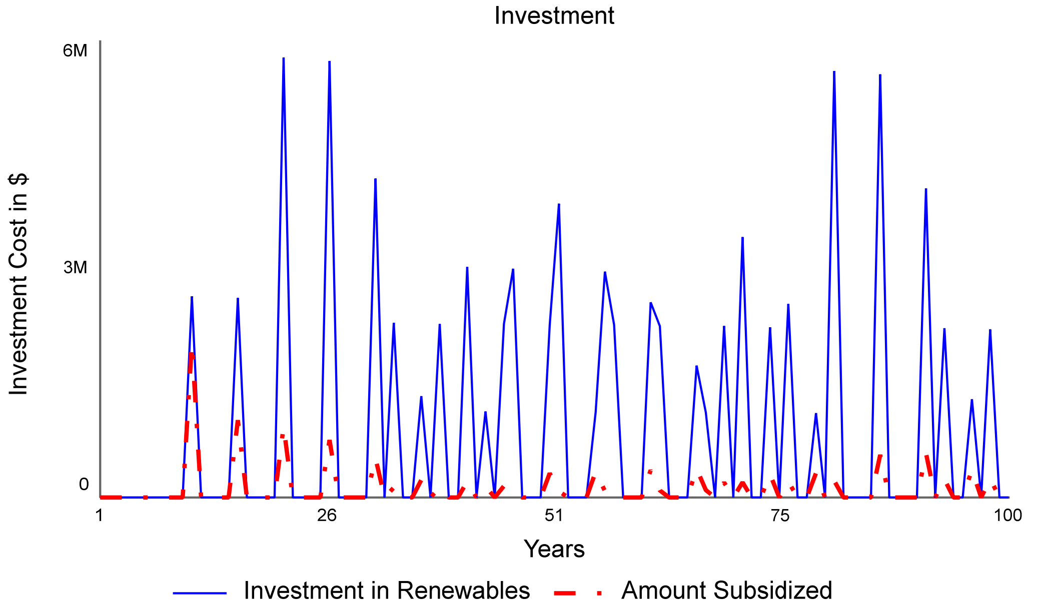

Figure 11. Investment and the amount subsidized. At the top is case 2, with the highest public pressure.

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 renewable 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.

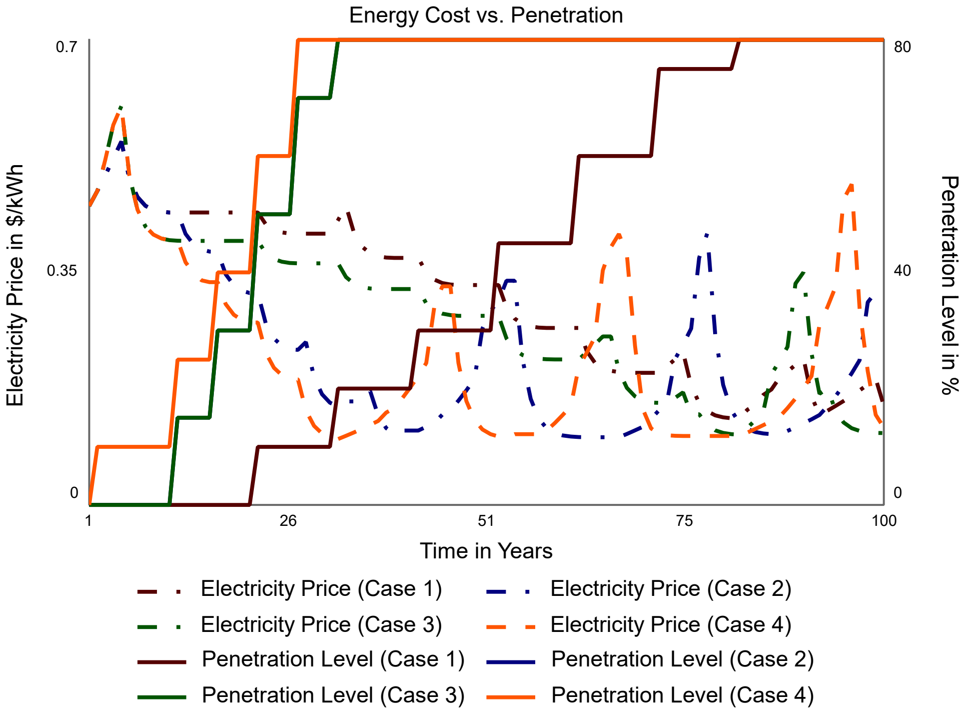

Figure 12. Energy costs vs. renewable penetration levels. The penetration level results from public pressure and policy, and the electricity price is the result. The solid lines represent the renewable penetration levels, and the dashed lines represent the electricity costs.

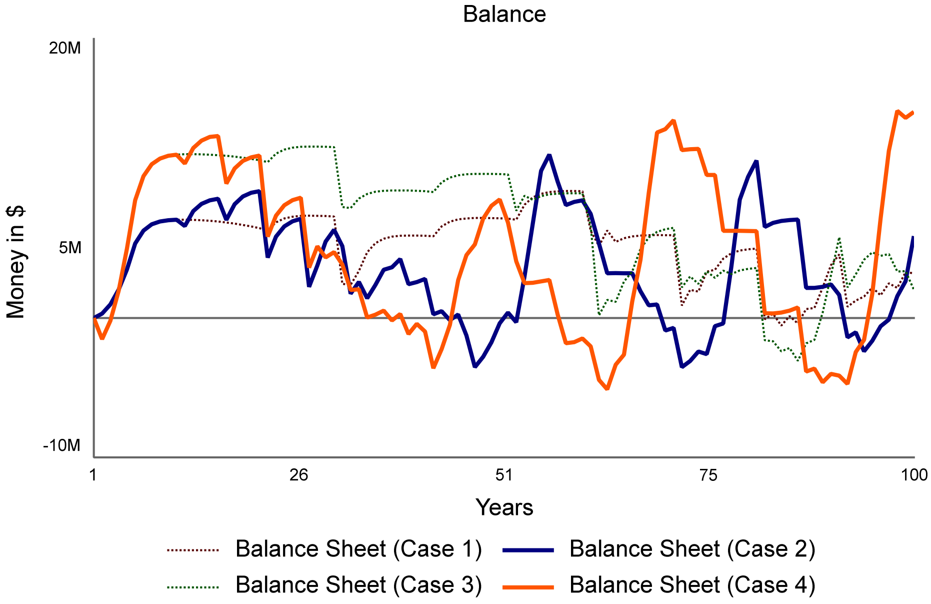

Figure 13. Balance of the utilities account: the solid lines represent the cases with fast energy transition. The dotted lines represent the slow transition cases.

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 CO_2 tax's impact is diminished.

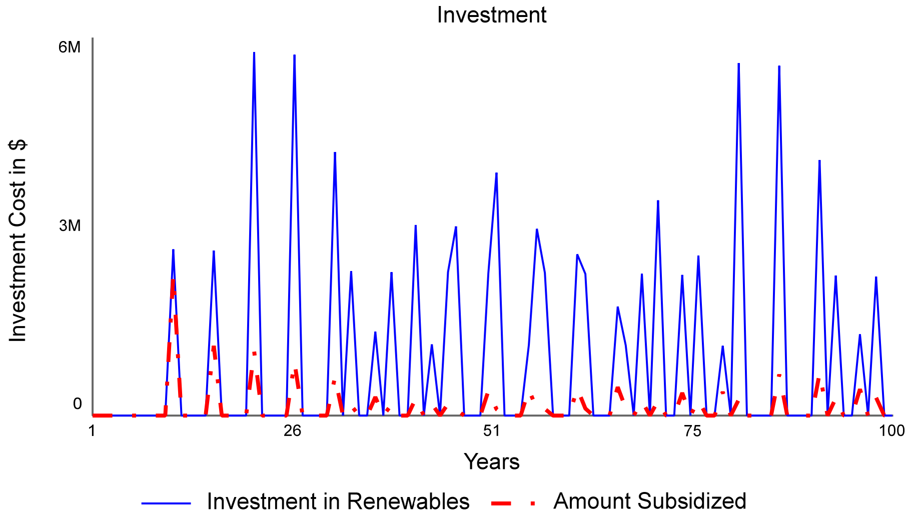

Figure 14. Investment and the amount subsidized. At the top is case 2, with the highest public pressure.

4.3. 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 shows that scenario 3 has a slower reduction in electricity prices compared 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.

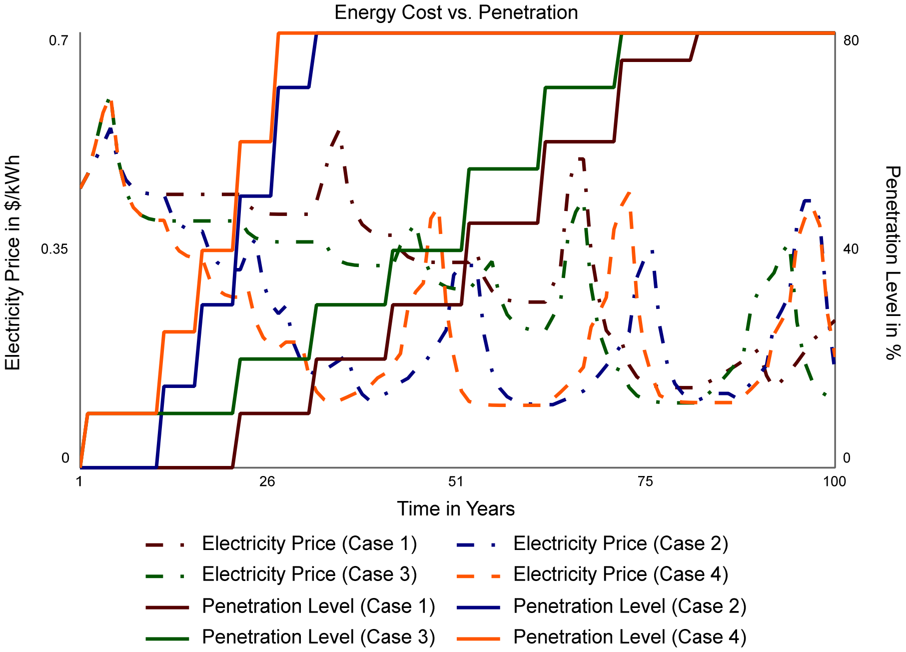

Figure 15. Energy costs vs. renewable penetration levels. The penetration level results from public pressure and policy, and the electricity price is the result. The solid lines represent renewable penetration levels, and the dashed lines represent the electricity costs.

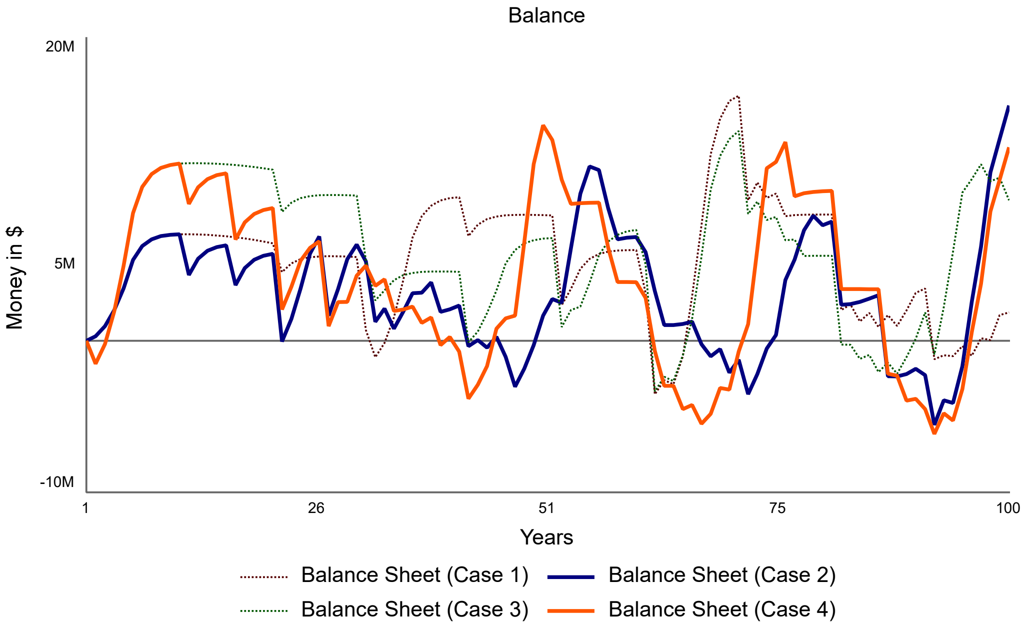

Figure 16. Balance of the utilities account: the solid lines represent the cases with swift energy transition. The dotted lines represent the slow transition cases.

5. 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 electricity prices for the associated cases. The results reveal a significant range in the average electricity prices across the simulated time, with costs ranging from USD 0.26 per kWh to USD 0.42 per kWh across all cases from scenarios 1, 2, and 3. Overall, the highest average electricity price for renewables is USD 0.05 lower per kWh than the average electricity price at 100% diesel. A comparison of Table 4 with the 100% diesel case (see base scenario, business as usual) reveals a significant cost savings. The average cost of generating electricity with 100% diesel would be USD 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 at relatively the same time. Nevertheless, case 4 is slightly more viable, as a result of the marginally lower costs. As for 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 those in 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. Thus, a faster transition is 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 portion shows the average electricity price. Diesel in the business-as-usual case has an average electricity price of USD 0.47/kWh. The middle represents the intercept of the linear regression over 50 years. The bottom portion 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. The color gives an indication from preferable green to not preferable red.

	Case 4	**Case 3**	**Case 2**	**Case 1**
	Average Electricity Price over 50 Years in USD/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 CO_2 tax. The allocation of a CO_2 tax to renewable energy projects would have the advantage of depending on CO_2 emissions. In the event that a high penetration level was reached, the CO_2 tax would become virtually obsolete, given that the proportion of CO_2 emitted by the vestigial generation of electricity using diesel would be negligible. Moreover, the CO_2 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 opposite directions. In all renewable cases, the electricity price moves downwards, while the business-as-usual case shows an upward trend in electricity prices. The subsidization of investment 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 in 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 transition 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, as well as 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 installed 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].

6. Conclusions

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 economic means, who are temporarily employed, 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 overarching 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 sooner, 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 involving 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, the suitability of SD for energy transition planning in remote communities. This can broaden the horizon to other remote areas, such as Southeast Asia, Africa, and Latin America. Moreover, elaborating on the method for such transition processes would increase confidence in the approach proposed 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, this 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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