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Renewable energy sources for arctic food sufficiency and sustainability

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One of the UN's 17 sustainable development goals (SDGs), SDG 7, is to "ensure access to affordable, reliable, sustainable and modern energy for all." This goal addresses the need for environmental sustainability while highlighting energy's vital role in promoting social and economic justice. It calls for sustainable, affordable, modern, and reliable energy usage for the health and well-being of society while mitigating climate change. Here, we briefly review available literature and data to examine how renewable energy, food security, and sustainability are interconnected in Arctic countries and regions, and how these regions can "ensure access to affordable, reliable, sustainable and modern energy for all" and progress towards achieving food self-sufficiency by integrating renewable energy sources into food production systems. We analyze several case studies to draw conclusions on how Arctic communities can become resilient, sustainable, and economically prosperous by promoting local food production while preserving cultural practices.

Importance of SDG 7 for the Arctic Region

The UN's SDG 7, to be achieved by 2030, i.e., five years from now, is to ensure universal access to affordable, reliable, and modern energy services while substantially increasing the share of renewable energy (Fig. 1). There will be a need for increased improvement in energy efficiency, enhancing international cooperation to facilitate access to clean energy research and technology, including renewable energy and energy efficiency, and advancing and promoting investment in energy infrastructure and clean energy technology[1]. Achieving several of the other UN SDGs, such as addressing food insecurity (SDG 2), promoting economic growth (SDG 8), improving health (SDG 3), and combating climate change (SDG 13), depends on SDG 7. A more sustainable, economically just future can possibly be achieved by increasing energy efficiency, investing in renewable energy storage, and guaranteeing access to affordable and clean energy. Addressing these issues requires a holistic approach that combines environmental sustainability, economic equity, and strategies tailored to the unique needs of Arctic communities, respecting their cultural heritage, way of life, as well as recognizing the interconnected global challenges of biodiversity loss, climate change, and food security, which are amplified in the Arctic[2].

The Arctic region

The definition of the Arctic Region is not fixed since its southern boundary can differ; it can be defined by the Arctic Circle (66° 33'N)[3] and by culture as the homelands of northern Indigenous peoples; based on temperature, where the monthly average temperature in the Arctic is below +10 °C throughout the year (by this definition, Quebec and Labrador are parts of the Arctic), even in summer[4]. This paper focuses on the Arctic Region parts of nine countries: Canada (Yukon, Nunatsiaq (Northwest Territories), Nunavut), Greenland, Iceland, Norway (Svalbard archipelago, Troms, Finnmark, and Nordland counties), Sweden (Norrbotten and Västerbotten), Finland (Northern Ostrobothnia, Kainuu, and Lapland), Faroe Islands, Russian Federation (Murmansk, Komi, Arkhangelsk, Yamalo-Nenets, Khanty-Mansi, Krasnoyarsk, Kamchatka, Magadan, Chukotka), and the United States (Alaska).

The Arctic Region is rich in natural resources with abundance of minerals like iron ore, copper, nickel, phosphates, zinc, diamonds, and a large reserve of oil and gas[5]. Distinct physical, climatic, and socioeconomic conditions, long distances, and sparse population characterize the Arctic. Additionally, the Arctic is home to abundant fisheries. However, the extraction of these is a challenging, high-risk endeavor and often threatens the fragile Arctic environment[6].

The Arctic landscape varies widely, ranging from cold to dry to tundra, including icecaps. Coastal areas are rich in habitats for seabirds, fish, marine mammals, and invertebrates. The land within the Arctic has seasonal snow and ice cover, with mostly treeless permafrost beneath the tundra[7]. Renewable energy resources, including wind, geothermal, marine, and hydrokinetic, also vary widely from region to region.

Traditionally, local food is obtained in the Arctic by hunting, trapping, herding, fishing, and collecting wild fruits. However, the dependence of Indigenous communities on the traditional way of food gathering is threatened by climate change, resulting in increased food imports from outside the region to supplement traditional supplies[8]. This dependence on imported food can be costly and lead to food insecurity[9].

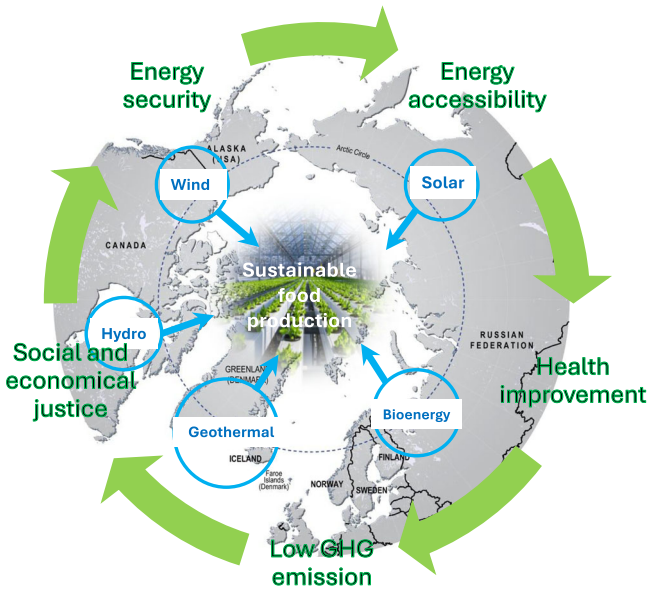

Fig. 1 | Addressing UN's SDG 7 through affordable, reliable, and renewable energy systems, which have implications for low GHG emissions, improved health, social and economic justice, energy security and accessibility, and sustainable food production.

Studies indicate that sustainable food production in the Arctic could be a viable option to address food insecurity, reduce global greenhouse gas emissions, mitigate climate change, and help achieve economic justice[10,11], all of which are relevant to SDG 7. For example, research by the Max Planck Institute for Evolutionary Anthropology and the Inuvialuit Regional Corporation reveals that using locally harvested food instead of imported food could save over 3.1 million Canadian dollars annually and reduce carbon emissions by approximately half[11]. The study highlights the importance of climate change policies that support local food systems. On the other hand, weakening these systems could lead to higher GHG emissions and threaten remote communities' health and food security. In another study, the potential of community gardens powered by renewable energy has been suggested to boost local food production[12,13]. It was discussed how Iceland's abundant renewable energy and urban population could create zero-emission community greenhouses, reducing the country's dependence on imported produce and carbon footprint while promoting social cohesion and resilience[12].

Arctic demography

Geographically, the Arctic makes up 20% of the Earth's surface mass, yet it is small from the standpoint of its around 4 million inhabitants[14], Indigenous people comprising about 10% of the total population[15]. Arctic demographic data highlights the complex relationship between climate sustainability and food security, particularly within Indigenous communities[16]. Consequences of climate change are reflected in demographic trends, resulting in changes in age structure, population distribution, migration, and disruption of traditional subsistence practices[17]. Rising food scarcity and environmental instability are driving young people to migrate south for education and job opportunities, while older generations are being forced to leave the North in search of improved living conditions[18]. Adaptation is becoming increasingly essential, and Indigenous Knowledge, along with community-led research programs, is crucial for understanding and addressing the rapid changes occurring in the Arctic[19].

Table 1 | Global food security index for selected arctic countries

Country	Global food security index 2022
Canada	7
Finland	1
Norway	3
Russia	43
Sweden	8
USA	13

Arctic demography, renewable energy resources, food security, and sustainability are deeply intertwined, as each factor influences the others in shaping the future of Arctic communities[16]. Ongoing climate change presents serious threats to traditional livelihoods and food sources, which are integral to Indigenous peoples' cultural identity and way of life. As warming temperatures and diminishing sea ice alter habitats, species that have long been relied upon for food are becoming increasingly difficult to access[20]. Rising Arctic temperatures are also affecting the availability of essential fish species. In Northern Norway, for example, the Atlantic cod (Gadus morhua) fishery plays a vital role for small-scale and Indigenous fishermen[21]. So far, warming has benefited this fishery, increasing cod stocks in recent years. However, further warming is expected to be harmful, as it is predicted to reduce the survival rates of juvenile cod[18]. As a result, many Arctic Indigenous Peoples relying on the cod fishery may face some of the highest rates of food insecurity even within this high-income nation, which exacerbates their vulnerabilities and impacts their cultural practices[22].

As briefly described, demography, renewable energy, food security, and sustainability are interconnected. Integrating traditional ecological knowledge with modern advancements underscores the importance of balancing heritage with innovation to promote food security and sustainable energy practices in the Arctic[16].

Food insecurity in the Arctic

The Arctic's harsh climate and inadequate infrastructure make it difficult to produce food reliably. The high cost of imported foods and energy, economic fragility, and lack of food storage and preservation infrastructure. Climate change and environmental disruptions contribute to food insecurity in most Arctic locations. Food safety is also an issue and dilemma for some communities where locally harvested food items (fish, meat, etc.) might contain contaminants above safe consumption levels due to long-range or local/regional pollution[19], underscoring the need for more accessible and affordable solutions for producing safe food. The following sections will review the food security and energy issues in selected Arctic regions, highlighting these communities' challenges and opportunities. Table 1 provides the Global Security Index for selected Arctic countries. This index evaluates countries based on several key factors: food affordability, availability, quality, safety, sustainability, and adaptation.

Alaska. One in seven Alaskans is food insecure[23]. Grocery stores have a three-to-five-day supply of most foods. Rural Alaskans import 95% of their store-bought food and experience the most food insecurity[24]; most imports are from the Lower 48, Canada, Mexico, and Pacific Rim nations.

Arctic Canada. Canada is ranked 7th on the Global Food Security Index[25]. Food insecurity is disproportionately worse in Arctic regions of Canada than elsewhere in the country, primarily due to geographic isolation, high transportation costs, and limited local food production. The climate is harsh, and locations are distant with less developed infrastructure. This makes imported food expensive. Furthermore, as mentioned earlier, climate change significantly impacts traditional food sources, further exacerbating food security challenges. Limited infrastructure, low-income levels, and high reliance on imported food also contribute to the higher rates of food insecurity in these regions. As a result, in Arctic regions of Canada, food insecurity reached 16.9%, 21.6%, and 57% in the Yukon, the Northwest Territories (NWT), and Nunavut, respectively, compared with a 12.7% average for the rest of Canada. Among Northerners, Indigenous peoples are particularly at risk of being food insecure[26]. It is estimated that 98% of food products consumed in the NWT and Yukon and 72–83% of those in Nunavut are imported from outside the territories. Most imports are from other provinces (about 60%), the United States, China, Mexico, and EU[27].

Finland. Finland ranks 1st out of 113 countries in the latest Global Food Security Index[25], considering the issues of food affordability, availability, quality, safety, sustainability, and adaptation. It should, however, be stressed that Finnish agriculture depends on various production inputs, such as fertilizers, fuel, feed proteins, and machinery, all dependent on a secure energy supply, and there are socio-spatial disparities between Southern Finland and the Arctic regions regarding food security[28]. The current geopolitical situation in the region is threatening the delicate balance in the food and energy nexus.

Norway. Norway ranks 3rd out of 113 countries in the latest Global Food Security Index[25]. Although Norway ranked 1st in the Sustainability and Adaptation categories, it ranked 51st and 28th in the availability and affordability categories, which affected its overall ranking. Over half of the meat consumed in Norway is imported. Fruits account for around 10% of the total value of agricultural and food imports. The EU accounts for 66% of the country's imports. Norway mainly imports from Brazil, Sweden, Denmark, and the Netherlands[28]. On the other hand, Norway exported 2.8 million tons of seafood in 2024, of which 48%, or 1.3 million tons, were from aquaculture[29]. In Northern Norway, grass-fed animal husbandry is the focus, mainly dairy, sheep, goats, and egg-laying hens, alongside the production of vegetables, potatoes, berries, and cereals like barley[10]. Greenhouses and tunnels designed for cold temperatures with limited sunlight are used to grow these plants[10].

Sweden. Sweden ranks 8th in the latest Global Food Security Index, scoring high in the affordability category[25]. The Federation of Swedish Farmers estimates that 50% of Sweden is food self-sufficient, defined as a nation's capacity to produce enough food to meet its needs without importing or purchasing extra food[9]. However, 91% of all fresh produce in Arctic Sweden is imported, primarily by plane. Northern Sweden must produce 11.5 kilotons of vegetables annually to be self-sufficient[30].

Greenland. Greenland has 17% self-sufficiency. A study from 2021 concluded that 1 in 10 Greenlanders are food insecure[23]. The Greenland government aims to increase food self-sufficiency by boosting local agricultural production, starting with potatoes. While the goal is to achieve food self-sufficiency by 2040, the plan lacks specifics on how this will be accomplished[31].

Iceland and the **Faroe Islands** have 53% and 22% food self-sufficiency, respectively[32]. There is no data for these three countries in the Global Food Security Index.

Russia. Russia is ranked 43rd on the Global Food Security Index overall, and 25th in the Quality and Safety category.

The overview above indicates that food security levels across Arctic regions vary widely. A study on food security across the Arctic region highlighted the various factors contributing to food insecurity for the Inuit population living in Alaska, Canada, Greenland, and Russia. The contributing factors are attributed to geographical location, pollution, climate change, and economic vulnerability[33]. Moreover, the disparities result from the varying economic and policy stances among the Arctic Inuit homeland's four nations[33].

Renewable energy potential and usage

The Arctic region has an abundance of renewable energy resources. The continuous daylight during the Arctic summers offers significant potential for solar energy generation, which can be stored in thermal energy storage systems for use during the dark winter months. Many Arctic regions experience strong winds, making small to medium-sized wind turbines an effective energy solution. Organic Waste from food production and local communities can supply energy through methane production via anaerobic digestion, bio-oil through pyrolysis, or by direct combustion. In addition to bioenergy, anaerobic digestion produces digestate, to be used as part of the growth medium and greenhouse food production. Smallholder hydroelectric power plants provide another viable energy option in areas where rivers are available. Geothermal resources, in regions with volcanic activity, can supply heating for greenhouses and electricity generation.

Currently, 80% of Arctic communities rely on diesel for their energy needs[34,35]. With its abundant renewable energy sources, the Arctic holds promise for renewable energy-based distributed energy systems (suited for isolated communities) that could contribute to sustainable and resilient energy generation and meet the region's expanding energy needs.

Although countries like Norway and Iceland are at the forefront of using renewable energy, most regions in the Arctic rely primarily on fossil fuels. Iceland has an abundance of hydropower and geothermal resources, which contribute significantly to renewable energy generation51. In 2021, approximately 87% of Iceland's energy supply was based on renewable sources, with hydropower constituting 73%, and geothermal energy comprising 27%[23]. Geothermal energy meets 90% of the country's heating needs, and 100% of its electricity is generated from renewables.

Greenland's total onshore wind power capacity potential is estimated at 333 GW, with a generation potential of 1487 TWh, assuming 20% of the ice-free area is available[36]. Hence, a 100% renewable energy system for Greenland is economically feasible[37]. The solar PV capacity potential for 20% of Greenland's ice-free area is 10.6 TW, with a corresponding electricity generation potential of 9137 TWh[38]. The study conducted by Galimova et al.[37] concludes that Greenland can become a major e-fuel and e-chemical exporter hub to Europe and Asia.

The Faroe Islands aim to achieve a 100% renewable electricity sector by 2030. The islands have significant potential for renewable energy, with an average annual wind speed of 10 m/s and rainfall reaching up to 3000 mm per year in some areas. The annual hours of bright sunshine are 840, paving the way for the future energy mix of wind turbines, solar panels, and pumped storage systems[39]. The Faroe Islands' renewable energy initiatives may offer valuable insights for other Arctic communities, but their direct transferability depends on each location's specific characteristics and challenges.

The Svalbard archipelago and the counties of Troms, Finnmark, and Nordland make up Northern Norway, where about 9% of Norway's population lives[23]. These regions have great potential for renewable energy, including hydro, wind[40,41] and solar[42]. In general, because of its wind power

resources and hydropower capacities, Norway has a significant percentage (more than 90%) of renewable energy production, supplying clean, renewable electricity[43].

Wind energy is heavily concentrated in Northern Ostrobothnia (Finland) and other provinces of Ostrobothnia. Most new wind farms were built in Northern Ostrobothnia, Ostrobothnia, and Southern Ostrobothnia in 2023[44]. Nearly 40% (950 MW) of the country's wind power is produced in Northern Ostrobothnia, and production capacity will continue to increase[45]. Kainuu, Finland, has enormous potential for bioenergy, considered Finland's largest renewable energy source, playing a pivotal role in reducing carbon emissions and ensuring energy security[46]. As of 2020, 14 wind power projects were in progress in Finnish Lapland, which would cover more than half of Lapland's electricity generation capacity[47]. Finland is at the forefront of smart grid technology worldwide, allowing for real-time power grid failure monitoring and household-specific, remotely readable, precise electricity usage metering. Furthermore, Finland is currently advancing toward the next stage of smart grid technology to accommodate the growing amount of small-scale generation, customer-level energy storage, electric vehicles, and programmable loads[48].

Northern Sweden supplies steady, entirely renewable energy through sustainable energy production methods, including wind turbines and hydropower. In addition to supporting sustainable energy infrastructure, smart grids that make storage and distribution easier are available[49].

In relative terms, Sweden, Norway, and Iceland have reliable, affordable, and sustainable energy because of their high levels of infrastructure development, effective policies regarding access to natural resources, financing systems, and energy transition strategies. Robust government-backed financing structures and substantial hydroelectric power infrastructure support Sweden and Norway's energy systems. Additionally, these countries have strong financial frameworks, including subsidies and incentives, and sophisticated grid systems that might not be as easily accessible in other areas, especially in more isolated areas. Therefore, while their progress is remarkable, it is crucial to understand that certain factors, such as greater investment, better infrastructure, and advantageous geography, support their success and may be difficult to duplicate in less developed or more remote locations.

However, it is also important to note that energy production in these regions impacts the Indigenous homelands. For example, the Sámi people across Sweden and Norway reported conflicts over land use and raised concerns about the violation of their rights, and expressed concern about environmental sustainability[50,51]. A report by Amnesty International reveals that Sámi lands are being treated as "sacrifice zones" in the pursuit of global climate goals and green financial interests, resulting in human rights violations[50].

Energy trade-off

In the Arctic, the environmental impacts (on the ecosystem and wildlife) of extracting oil and gas have been a subject of discussion[52]. Further expansion of the oil and gas infrastructure may lead to additional adverse environmental impacts, habitat loss, disruption of animal migration patterns, and the potential for oil spills[52]. It is believed that transitioning to renewable energy sources can lead to a sustainable future[53]. Several considerations regarding land use, environmental impacts, and animal migration patterns need to be taken into consideration when, for example, wind turbines, hydropower plants, and photovoltaics are installed[3].

The need for collaboration and knowledge sharing

Although Arctic communities are remote, they are interconnected within a broader regional network, all facing similar energy challenges, including isolation and the impacts of a changing climate[54]. Hence, international collaboration and knowledge transferability regarding energy transition offer significant advantages, helping communities address these challenges together effectively[54]. Examining case studies from various Arctic regions makes it possible to uncover commonalities and potential solutions to the shared energy transition issues they face[54]. While potential lessons can be drawn from each country, it's essential to recognize that each Arctic region has unique challenges. Larger or more remote communities may face logistical difficulties (e.g., importing materials), harsher environmental conditions (e.g., lower temperatures and ice cover), and more limited infrastructure. In the following section, we will discuss several case studies from which key takeaways can be drawn that can be useful for future renewable energy projects in the Arctic.

Case studies in Alaska[55]

A case study by Anderson[55] explored the challenges and benefits of implementing renewable energy-based distributed energy systems in Alaskan communities. It compared six communities without renewable energy systems and five with them, highlighting several challenges and needs. Utqiagvik, Noorvik, Angoon, Tuluksak, Tanacross, and Nikolski were the communities studied without renewable energy systems installed. These communities were interviewed to assess their views on implementing renewable energy systems in their communities in the future. The communities identified various needs and challenges associated with developing renewable energy-based systems, mainly technical, human capital, economic, and social and political issues.

1. *Technical*: Communities need accurate resource assessments and systems that integrate well with existing infrastructure. Customized solutions may be necessary over off-the-shelf options.
2. *Human capital*: Adequate training and skilled project managers are essential. Small, easy-to-maintain systems, like solar PV and batteries, can serve as stepping stones to larger projects.
3. *Economic*: Energy subsidies for fossil fuels reduce incentives for renewable energy adoption and may increase rates for non-subsidized customers.
4. *Social and political*: Continued involvement and community support are essential. They added that prior bad experiences with government initiatives can erode confidence, necessitating attempts to mend fences and uphold local values.

The study also noted that slow federal permitting, inflexible funding, and high development costs could delay or compromise projects. Successful projects require communication on benefits, collaboration, and coordination among stakeholders.

The same study also interviewed six communities that had installed renewable energy systems[55]. These were Galena, Kotzebue, Shungnak, Kobuk, Kodiak, and Kongiganak communities.

In Galena, AK, biomass accounts for 75% of the heating at the Galena Interior Learning Academy, which serves 200 students. This initiative's success was driven by robust community involvement, with local leaders and residents collaborating closely. The project also generated local employment opportunities, including in construction, labor, and system maintenance, fostering long-term empowerment within the community.

Some of the operational technical challenges encountered in this project included wood-harvesting equipment often malfunctioning when operating in temperatures as low as −30 °F. Additionally, the boiler's automated feed system occasionally experienced issues requiring the regular cleaning of the heat exchanger due to the buildup of mill scale, a magnetite coating that forms on hot steel surfaces. Involvement in decision-making

and hiring a local workforce helped foster community support. The system has remained operational despite technical challenges, like equipment breakdowns in extreme temperatures and boiler issues.

Kotzebue, AK. Kotzebue's renewable energy project combined 2250 kW from wind and 576 kW from solar PV. To effectively operate these systems, the community underwent extensive technical training, with remote support enhancing local expertise. The project reduced the need for diesel storage and enabled Kotzebue to lease surplus fuel storage, fostering local competition and lowering living costs. While residential electric bills remained stable due to reduced power cost equalization (PCE) subsidies, nonresidential customers experienced significant savings.

Key lessons learned from the project include:

- Ensure proper equipment selection and installation.
- Overbuild to meet both base load and contingency requirements.
- Use a sufficiently large battery to handle winter load demands.
- Seek grant funding to minimize local financial risks.
- Clearly communicate the system's benefits, particularly regarding savings for nonresidential customers.

This initiative has strengthened Kotzebue's technical capacity, boosted its wealth, and instilled a sense of pride, positioning the community as a leader in renewable energy development.

Shungnak and Kobuk, AK. Shungnak and Kobuk partnered as an independent power producer (IPP) to develop a renewable energy project, leveraging data from a previous project in Buckland and Deering. A pilot heat pump project, funded by the Coastal Impact Assessment Program, demonstrated the technology's viability in local conditions. They are seeking funding to expand heat pump installations and reduce electricity rates. Households are expected to save $2000–$2500 yearly from heat pumps.

The solar PV system generates 200 MWh annually, offsetting 14,300 gallons of diesel. The communities aim for a renewable fraction of 11–15%, with plans to reach 30%. Plans include upgrading the inverter to 500 kW for a 300-kW winter peak load and adding a 100-kW wind turbine.

Challenges and lessons learned. Strong relationships with suppliers, consultants, and contractors are key to success. Shungnak and Kobuk benefited from good planning and the local tribe's control over the project, simplifying land and equipment ownership. Heat pumps are more cost-effective when building new homes, with fuel prices being high enough to justify the investment. Increasing the energy eligible for PCE support can enhance the financial benefits of electrical heat pumps.

Kodiak. In 2000, Kodiak's power was mainly supplied by the Terror Lake hydropower plant, with diesel generators filling the gaps. While hydropower was more cost-effective, it relied on rainfall, causing price fluctuations. This unpredictability prompted the Kodiak Electric Authority (KEA) to create a 95% renewable energy system, at a cost comparable to or lower than diesel.

In 2009, the Kodiak Electric Authority (KEA) purchased the Terror Lake hydropower plant from the Four Dam Pool Power Authority for $38 million, funded through a USDA loan. This acquisition enabled modifications to transition toward a renewable energy system. KEA integrated hydropower with wind energy, collaborating with the local community and conducting detailed wind resource assessments. Over the next 16 years, the system was upgraded in phases, incorporating wind turbines, battery storage, and flywheels to stabilize the grid.

KEA exceeded its goals, achieving 99% renewable energy, 85% from hydropower, and the remainder from wind. Diesel generators are now seldom used, and wind turbines prove more cost-effective than diesel, significantly lowering energy costs. The success of this project is attributed to meticulous planning, strong community support, and lessons learned from earlier setbacks. KEA now plans further expansions to meet growing demand and maintain long-term reliability.

Kongiganak (Kong). After the 2008 fuel price spike, Kongiganak, which had been entirely dependent on diesel, transitioned to renewable energy. Lacking hydropower and solar resources, the village opted for wind energy and formed the Chaninik Wind Group (CWG) cooperative with neighboring communities to secure funding and build local capacity. Five 95-kW wind turbines were installed in 2009; by 2012, they were fully operational. These turbines, designed to withstand harsh Alaskan winters, were integrated into the grid with enhancements for greater durability and efficiency. In 2011, 50 electric thermal stoves and a wind-diesel SCADA system were added to reduce diesel consumption. A lithium-ion battery for voltage regulation was introduced in 2018. Today, Kongiganak uses 56,000 gallons of diesel annually, down from 80,000, while electric thermal stoves have cut heating oil consumption by up to 50%. The community is working towards achieving 100% renewable energy, with plans for a 200-kW solar farm and wind turbine upgrades.

Key challenges and lessons learned include training and retaining local technicians, which are essential in all project phases. Local expertise helped address technical issues like SCADA system failures and battery upgrades. Community support, clear communication, and minimal conflict were crucial for the project's success. The initiative has also built technical capacity, supporting renewable energy installations in other communities.

Case studies in Iqaluit (Canada), Tiksi (Russia), and the Faroe Islands[54]

The case studies of Iqaluit (Canada), Tiksi (Russia), and the Faroe Islands provide valuable insights into the energy systems of remote Arctic communities[54]. They showcase unique challenges and shared experiences in the transition to renewable energy. By examining these locations side by side, the authors conclude that there are diverse approaches to energy transition and the complexities faced by Arctic regions. A summary of the study[54] is provided below.

Diesel is the primary source of electricity and heating in Iqaluit, Nunavut. The means of transportation include trucks, sea barges, and airplanes. High emissions, pollution, and adverse health effects are some of the consequences of using and transporting diesel fuel. Switching to renewable energy is complicated because of the aging infrastructure. Through programs like the "Indigenous Off-Diesel Initiative," the Canadian federal government is bolstering support for renewable energy in rural towns. However, Iqaluit's remote location makes it difficult for the community to adopt new technologies.

The Faroe Islands have committed to achieving 100% renewable energy by 2030, removing their reliance on imported oil and gas. The islands have attracted international investment to develop wind, tidal, and hydropower technologies, achieving over 50% renewable energy use by 2022. Significant infrastructure investments and innovative projects like wind-powered heating systems and tidal kites support this ambitious transition[54].

Tiksi, in the Russian Arctic, offers a hybrid energy model, combining diesel with wind power. The town's energy system, which includes a 900-kW wind park and energy storage, has reduced diesel consumption by 500 tons annually[54]. This project is part of a broader effort to diversify energy sources in Russia's remote regions, highlighting the potential for hybrid systems as a viable path for other Arctic communities.

The Sámi experience in Norway[56]

A case study on how the Sami people perceive renewable energy systems adoption indicates that while the Sámi support renewable energy adoption, they oppose projects on their lands that threaten their cultural way of life[56]. They argue that developments like wind turbines and hydroelectric dams disrupt reindeer herding, a key aspect of their culture. Wind turbines, in particular, can block migration routes and ruin grazing areas. Sámi organizations argue that some renewable projects may harm the environment more than help. They advocate for upgrading existing infrastructure rather than building new projects on Sámi land.

Legal cases, such as one in Norway, highlight the negative impacts on reindeer herding. While Sámi groups often receive compensation, they fear long-term consequences, including more disruptions after decommissioning wind turbines. Sámi leaders stress that losing their land equates to losing their culture.

Though consultation is required by law, Sámi groups feel their input is often ignored, and decisions are made with little regard for their rights. The Sámi are increasingly turning to courts, where recent rulings suggest growing recognition of their Indigenous rights. However, they face significant challenges, as national policies often prioritize renewable energy projects over cultural preservation.

Russia[57]

In Russia, significant fossil fuel subsidies create a major disincentive for renewable energy development and reinforce the interests of national oil companies[57]. Despite these challenges, there has been growing interest and progress in adopting renewable energy across the Russian Arctic[57].

The Russian case has unique characteristics. First, financial mechanisms supporting renewable energy systems are limited to the capacity market since 2013, and the retail market since 2015[58,59]. In Russia's centralized governance system, regional laws are required to align with federal policies, which means local governments have limited autonomy in enacting their own laws[60,61]. Consequently, the effectiveness of regional implementation of federal policies varies across different locales.

Furthermore, Russia's renewable energy sector heavily depends on foreign technology, and the 2014 Ukrainian crisis and resulting international sanctions have exacerbated this dependence by limiting access to foreign renewable energy technologies and raising costs due to currency devaluation, thereby diminishing the attractiveness of renewable energy investments[62].

Key takeaways

- Renewable energy projects in these regions must respect Indigenous land rights, cultural values, and livelihoods. Ensuring no harm to their rights, way of life, or environment is key. Meaningful consultation and active Indigenous involvement in planning and decision-making are essential for sustainable, equitable energy development.
- Although there is considerable potential for renewable energy in the Arctic, different Arctic countries have diverse adoption rates. Building renewable energy systems in the Arctic presents technical, social, economic, political, and administrative challenges, intricate funding systems, equipment transportation challenges, and drawn-out permitting procedures[55].
- Properly implemented, renewable energy initiatives can enhance local wealth, skills, and job satisfaction, while saving money and improving energy reliability. By reducing reliance on costly imported fossil fuels and lowering electricity and heating costs, they can protect communities from volatile weather and unstable petroleum markets[55].
- Financial barriers can be overcome with grants and loans, while remote technical challenges can be addressed by training local workers. Technical risks can be minimized through careful engineering, experienced partners, and ensuring that the technology suits Arctic conditions.
- The case studies illustrate how energy transitions vary across different Arctic regions and emphasize the need for tailored solutions that balance reliability, sustainability, and local context.
- Regional collaboration in the Arctic can drive innovation and accelerate SDG 7 by advancing energy solutions for Arctic climates, such as hybrid systems and portable, modular energy systems. Partnering with small utilities and residential prosumers can help address energy challenges and position the Arctic as a model for remote, extreme environments[63].

Conclusion

The climatic conditions and isolated locations make it difficult for the Arctic to have a centralized energy infrastructure, necessitating the development and implementation of alternative energy solutions tailored to the unique challenges of the Arctic[64]. Renewable energy-based solutions can address this issue, increase energy independence and sustainability, and promote Arctic food production, particularly in controlled settings like greenhouses or year-round containerized systems. While implementing renewable projects can present challenges, they can be addressed through community support, education, and communication with trusted leaders. If implemented correctly, with consultation with communities, clean energy can effectively support food production in Arctic regions, particularly in the context of sustainable agriculture and food security[10], offering several benefits, such as reducing reliance on fossil fuels, lowering energy costs, and minimizing environmental impacts[65–67]. While countries like Iceland, Sweden, and Norway have progressed toward SDG 7, other Arctic regions can accelerate their renewable energy transitions to meet energy needs and contribute to global climate change efforts.

Data availability

No datasets were generated or analysed during the current study.

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Competing interests

The authors declare no competing interests.

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