Geothermal Energy and Resilience in Arctic Countries

Amanda Kolker, Robbin Garber-Slaght,
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and Hannah Pauling

National Renewable Energy Laboratory

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List of Acronyms

AEO	Arctic Energy Office
BAU	business as usual
BESS	battery energy storage systems
CHP	combined heat and power
DER	distributed energy resource
GCCU	geothermal combined cycle units
GDH	geothermal district heating
GHG	greenhouse gas
GHP	geothermal heat pump
GSHP	ground-source heat pump
NREL	National Renewable Energy Laboratory
O&M	operation and maintenance
ORC	organic Rankine cycle
PCE	Alaska's Power Cost Equalization program
PGV	Puna Geothermal Venture
SCADA	Supervisory Control and Data Acquisition

Executive Summary

The eight Arctic countries—Iceland, Canada, Denmark (Greenland and the Faroe Islands) Norway, Sweden, Finland, Russia, and the United States (Alaska)—have diverse energy systems, but can be split into two distinct groups based on energy characteristics. The first group includes systems in Europe (Finland, Norway, Sweden, and Iceland), which are heavily **grid-connected**. The second group includes the United States (Alaska), Canada, Russia, and Greenland, which have grid-connected energy systems in their more densely populated southern regions, but are also defined by the **prevalence of remote microgrids.** Energy sources for heat and power vary across grid-connected communities in the Arctic nations. The primary energy source for remote communities, on the other hand, is almost exclusively diesel. This is true for both heat and power.

Despite these and other key distinctions, Arctic countries share many commonalities with regard to their energy systems. One is a fundamental need for heat. Heat and electric energy are linked in most communities—remote, rural, and urban—and those linked systems are increasingly vulnerable to disruptions. Several of the Arctic countries use baseload renewable energy resources for heat and power. Iceland uses geothermal and hydroelectric; Canada, the United States, Sweden, Norway, and Finland use hydroelectric. Utilization of baseload renewable energy resources on-site for combined heat and power appears to enhance the resilience of communities in Arctic countries with high penetration of those resources. On the other hand, reliance on diesel by remote communities in other Arctic countries may be amplifying vulnerabilities.

Although geothermal energy is currently used in all eight Arctic countries, resources are poorly mapped, and finding detailed information can be difficult. Despite this, geothermal energy provides heat and sometimes electricity at the utility scale and at the microgrid scale. Geothermal electricity is produced in Iceland, Russia, and the United States (Alaska). Direct use of geothermal heat is applied in Iceland, Russia, United States, Canada, and Norway. Geo-exchange is used in Sweden, Finland, Norway, Canada, and the United States.

In this paper, we reframe geothermal heat and power systems as integrated energy systems, asking the question: are integrated geothermal energy systems—where available and economic—resilient solutions for communities in Arctic countries? We identify resilience attributes of integrated geothermal energy systems, with a focus on microgrids and small-scale applications. Based on the high-level, qualitative analysis presented in this paper, the answer appears to be yes. Further work should prioritize refining our understanding of geothermal resources in Arctic countries, because development of the most economic geothermal resources in Arctic countries has the potential to enhance the energy resilience of its residents, whether in a grid-connected or remote off-grid context.

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1 Introduction

Energy systems in Arctic countries are in transition. The eight Arctic countries, defined in this paper as members of the Arctic Council, include: Canada, Denmark (Greenland and the Faroe Islands) Finland, Iceland, Norway, Sweden, Russia, and the United States (Alaska). Arctic countries are particularly vulnerable to climate-change-related hazards, including sea level rise, thawing of permafrost and sea ice, changing wildlife migration patterns, and the increasing unpredictability of seasons and weather patterns. A recent study published in *Nature Climate Change* found that the Arctic is currently experiencing abrupt climate change: temperatures rose by 1 degree Celsius every decade over the past 40 years in the Arctic Ocean (Jansen et al. 2020). These changes, along with other related ones (e.g., geopolitical) can cause disruptions to energy systems and their support infrastructure. Due to the remoteness of many communities in Arctic countries, it can be more challenging than elsewhere in the world to recover from the natural disasters that are increasing in frequency and magnitude. Reliance on fossil fuel—currently widespread in many Arctic countries—is under scrutiny, increasing the value of baseload renewable resources, such as geothermal energy.

Indigenous Peoples in Arctic countries, whose voices are not always included in energy and infrastructure planning even in their own communities, are emphasizing the need to take an integrated approach to the challenge of building resilience. To "become stronger and more resilient," there is a need to integrate Indigenous knowledge into frameworks for adaptation planning guided by Western scientific approaches (Bahnke et al. 2020). An integrated approach to energy systems analysis would frame energy systems within the context of other important pieces of a healthy community—access to food, housing, energy, infrastructure, water/sewer systems, community/cultural health, and economic development.

Integrated energy systems utilizing geothermal heat and power could be a resilient energy solution for communities in Arctic countries near geothermal resources. Geothermal energy has several resilient qualities when compared to other sources of energy. Some of the attributes that make geothermal energy resilient include:

1. **Utilization of an on-site resource for energy:** this eliminates the need for the transport of fossil fuels and risks of supply chain disruption.
2. **A high capacity factor** (~80%–90% for power): this makes geothermal energy more comparable to fossil fuel power plants than other renewable energy technologies, with the ability to provide stable and reliable baseload power and heat (Gehringer and Loksha 2012).
3. **Long lifetime:** geothermal energy developments can include resources able to provide baseload heat and power for several decades and in some cases centuries.
4. **Low operational costs:** while geothermal energy installations have relatively high capital costs, they have low operational costs.
5. **Load flexibility:** geothermal power plant loads can be increased or decreased relative to demand (Geirdal 2015). These qualities are particularly advantageous in Arctic countries, where remoteness and cold climates pose great threats to functionality and resilience of energy systems.

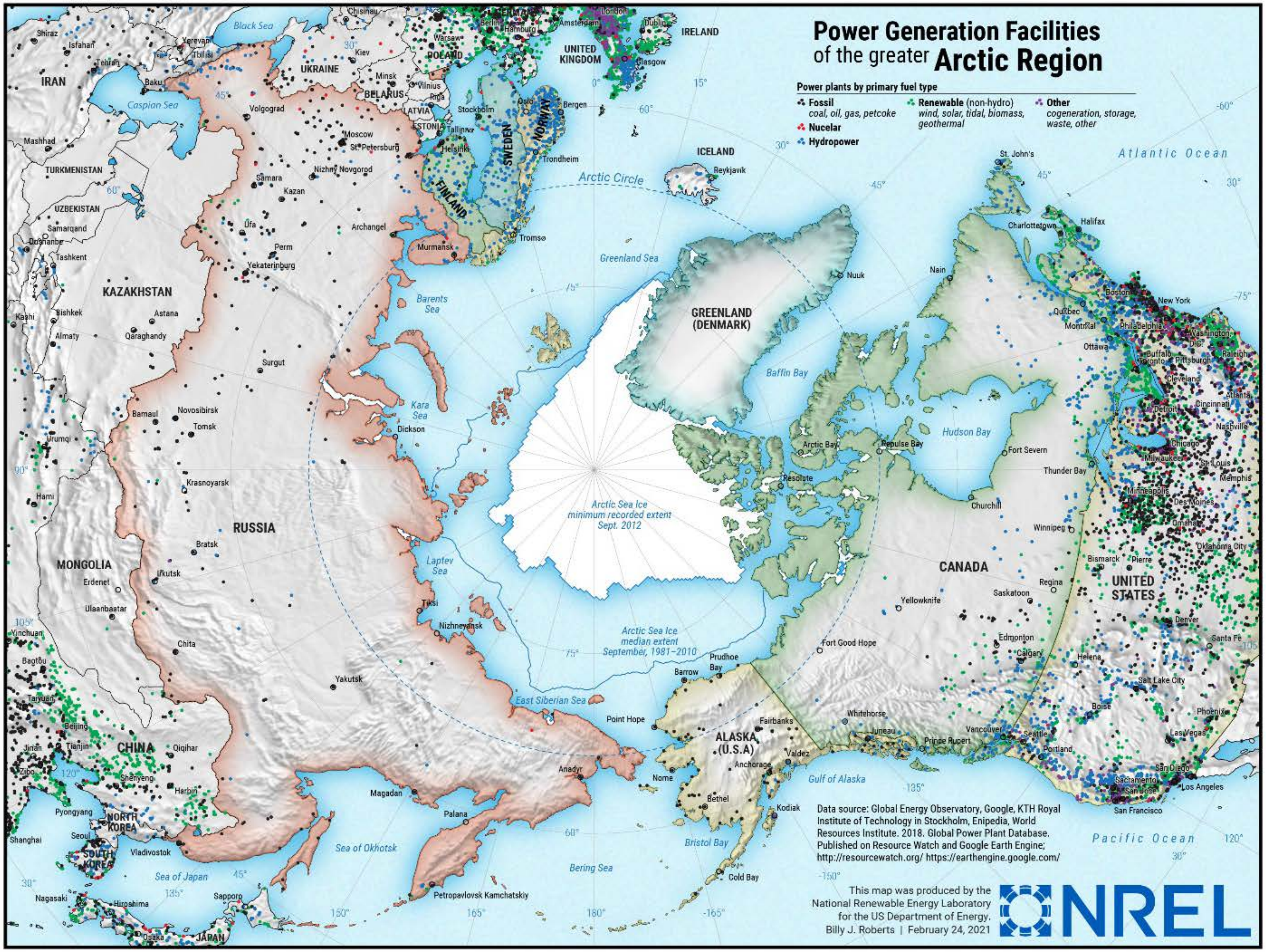
Geothermal energy also has many ancillary benefits to its users, including: (1) low greenhouse gas (GHG) **emissions** and **small environmental impact**; (2) by supplying both heat and power (when available and designed to do so), geothermal energy provides **economic development and food security** opportunities to remote communities who would otherwise be dependent on imported food; (3) increased **energy security** and **energy equity due** to local supply of heat and power; and (4) **low land use** per unit of energy produced.

This paper provides an overview of the energy resilience challenges faced by Arctic countries, reframing Arctic energy systems as integrated heat and power systems. The resilience attributes of integrated geothermal heat and power systems are applied to examine how deployment of geothermal technologies could enhance energy resilience in Arctic countries, with attention to impacts on food security, energy equity, environmental and climate justice, and other market externalities. The question this paper seeks to answer is: *are integrated geothermal energy systems—where available—resilient solutions for communities in Arctic countries*?

1.1 Energy Use in Arctic Countries: Overview

Arctic countries have diverse geopolitical systems, ecosystems, and equally diverse energy systems. Many of the communities in Arctic countries are small and remote. These remote communities are rarely connected to a larger energy grid and must create and supply their energy locally. The majority (about 80%) of this energy is produced via fossil fuels (e.g., diesel, natural gas, and coal) (de Witt, Stefánsson, and Valfells 2019). Iceland and Norway are the exceptions in the Arctic, with almost 100% renewable energy sources. Iceland's grids are powered by geothermal and hydroelectric (Rud et al. 2018; see Figure 1). The three Scandinavian Arctic nations—Norway, Sweden, and Finland—have national grids supplying power to nearly all residents. Electric grids in those countries are primarily powered by hydroelectric, coal, and hydrocarbons.

Small local electrical generation systems are often called microgrids. A microgrid—sometimes called a minigrid—is a group of interconnected loads and distributed energy resources (DERs) that can either be attached to a centralized grid or operate independently in "island-mode" (i.e., it can be unconnected to a grid or connected to a grid but able to temporarily disconnect and operate independently; Anderson et al. 2017). In the four large land-mass Arctic countries—Russia, Greenland, Canada, and Alaska in the United States—microgrids are prevalent, serving loads from a single building to an entire community. Diesel fuel provides power and heating for remote microgrids; diesel generators have a long track record and are considered reliable. Diesel itself is usually imported via barge in the ice-free summer months in remote Arctic communities. Electricity use in Arctic countries mirrors worldwide trends: increased uptake of electrical appliances and goods has steadily increased the need for power supply over the past half century. The pan-Arctic map in Figure 1 shows the locations and relative size of power generation facilities, grouped by primary fuel type.



Data source: Global Energy Observatory, Google, KTH Royal Institute of Technology in Stockholm, Enipedia, World Resources Institute. 2018. Global Power Plant Database. Published on Resource Watch and Google Earth Engine; http://resourcewatch.org/ https://earthengine.google.com/

This map was produced by the National Renewable Energy Laboratory for the US Department of Energy.
Billy J. Roberts | February 24, 2021

Figure 1. A pan-arctic view of power generation facilities showing power plants by primary fuel type. Only Arctic communities with power data are mapped.

Map credit: Billy Roberts, NREL

Despite the attention given to power generation, space heating is the dominant energy use in many communities in Arctic countries. Heating in remote communities is also usually sourced from diesel (Fay et al. 2013; Thayer 2019). Urban communities in Nordic countries use centralized heat and power from district heating systems (Lund and Toth). In Iceland, geothermal heat district heating systems are prevalent (Richter 2016).

Diesel fuel has traditionally been used in Arctic countries both for providing baseload energy to community microgrids as well as backup power to large-scale utilities, but renewable energy sources are gaining prominence for two reasons. First, the increase in the number of high-impact and high-cost natural disasters has exposed the fact that existing approaches to energy resilience are not sufficient in many communities (Anderson et al. 2017), particularly remote communities in Arctic countries. Power outages in remote villages in Alaska, for example, have had lasting effects on community infrastructure, including interdependent systems such as water supplies (Williams 2021; Associated Press 2020). Numerous vulnerabilities in Alaskan energy systems were exposed during these outages, including fuel supply interruptions, lack of refueling options for backup diesel generators, unreliable operation of backup generators, and aging infrastructure (Marqusee et al. 2017).

1.2 Key Issues, Challenges, and Opportunities

Remote communities in the Arctic are isolated and are often limited in local resources. Similar in this respect to island nations, remote communities in the Arctic face vulnerabilities related to dependency on the import of many basic goods and materials. Long diesel supply lines make the use of diesel quite expensive in the Arctic, and locations with access to natural gas and natural gas pipelines are rare, amplifying adverse effects on supply chains from climate change-related disruptions (Daw and Stout 2019).

Indigenous Peoples who have lived in the Arctic for a millennium face multiple existential threats posed by Arctic change, including **food security** and impacts on **community infrastructure** (Bahnke et al. 2020). The primary traditional food resources for many communities in Arctic countries come from the land, air, and sea, with rural communities gathering a large portion of their food resources locally. That practice is threatened by the diminishing availability of subsistence food resources, among other factors. In the words of a Yup'ik resident of Oscarville, Alaska: "We were once migrant people, traveling with our food resources. We are no longer able to do so and climate change is moving our food further away" (Schaeffer et al. 2018). These two existential threats are inextricably linked to energy systems.

In dominantly grid-connected Arctic countries such as Sweden and Finland, energy challenges and opportunities are mostly related to meeting aggressive carbon emission reduction targets. Sweden and Finland have two of the most rigorous carbon pricing laws in the world, which has allowed these countries to reduce carbon emissions in recent years. A large portion of the energy supply in these countries comes from hydropower and nuclear, both of which have challenges of their own. Hydropower is impacted by water scarcity or drought, and there are concerns about environmental and ecological sustainability, some of which can be mitigated with measures such as fish-friendly hydro turbines. Nuclear energy faces challenges related to fuel storage and disposal (and associated social acceptance challenges), as well as high capital and operating costs.

At the same time, communities in Arctic countries—remote, rural, and urban—are seizing opportunities to adapt to the rapid changes they are experiencing. Inclusion of Indigenous voices in conversations about the future of Arctic energy is recentering the dialogue around values of self-reliance and resourcefulness using local resources. Native Alaskans, Canadian First Nations/Inuit/Métis, the Sami people of Scandinavia, and other Indigenous Peoples make up a significant portion of energy use in Arctic countries and are helping to find acceptable solutions.

In 2021, it is becoming impossible to consider the use of diesel fuel without attention to environmental costs. Concerns about environmental and health impacts of widespread diesel fuel use (impact of transit and infrastructure, impact of fuel spills and other cleanup, and of course GHG emissions on the local and global ecosystem) are becoming internalized into energy planning decisions. This is making renewable energy sources an attractive alternative to fossil fuels.

1.2.1 Renewable Energy Use in Arctic Countries

The combination of fuel supply interruptions, increased cost-effectiveness of renewable energy plus battery energy storage systems (BESS), and carbon pricing in some Arctic countries has generated significant interest in using renewable energy plus BESS technologies (primarily photovoltaics and wind turbines). The grid-connected benefits of renewable energy and BESS microgrids include offsetting bulk energy purchases, reducing peak demand charges, performing energy arbitrage, and providing ancillary services. With the appropriate inverters and controls, these same systems can be islanded to form a microgrid, along with diesel generators (Anderson et al. 2017).

The most widely used renewable energy technology in Arctic countries is hydroelectric power (hydropower). Some smaller-scale communities in Iceland, Canada, the United States, and Greenland have access to hydropower, but the large capital cost of hydropower makes it difficult for most remote microgrid communities. Coastal Alaskan communities have been integrating wind into their microgrids. Cold dense air can increase the power output of a wind turbine up to 20%, but maintenance is key to long-term success of remote wind (de Witt, Stefánsson, and Valfells 2019). Solar photovoltaic technologies are mostly small scale in Arctic countries because solar energy is limited in the high-demand winter season. Solar photovoltaics comprise less than 1% of the power generation in Arctic countries (de Witt et al. 2021).

Iceland's renewable energy production involves both geothermal and hydropower, and the country's unique geology facilitates the use of geothermal energy for 62% of total Icelandic energy production (Huttrer 2020). Altogether, Iceland's annual energy production in 2020 from eight operational geothermal power plants was 24.2% of the total geothermal power production in the Arctic (calculated from Huttrer 2020). Half of these power plants co-generate heat with power, recycling geothermal waters for district heating, public hot water, and seawater drying (Ragnarsson 2015). Overall direct use of geothermal energy in Iceland is 67.7% of geothermal direct usage in the Arctic, the majority of which goes toward district heating, but it also is used for greenhouses, fish farming, and snow melting (calculated from Huttrer 2020).

1.3 Resilience

Resilience is the ability to anticipate, prepare for, and adapt to changing conditions and withstand, respond to, and recover rapidly from disruptions.

Resilience is defined many ways. A commonly accepted definition for the term, proposed by the National Academy of Sciences, is "the ability to prepare and plan for, absorb, recover from, and more successfully adapt to adverse events" (NRC 2012). Hotchkiss and Dane (2019) provide a similar definition 2019 that has been widely adopted in research at the National Renewable Energy Laboratory (NREL) (see definition in text box, above). Resilience is a broad topic that simply asks the question, "is the system, component, community, etc. prepared to handle a major disruption?" The disruption can be the result of any number of things and is thus difficult to prepare for. Any system needs a few characteristics to be resilient to varied disruptions.

Because resilience is defined differently by different stakeholders, system designers and community planners consider various *attributes* of resilience. These include: **robustness**, the level to which assets are hardened against disruptions; **recoverability**, the extent to which assets can bounce back from disruption; **resourcefulness**, the flexibility of the system to adapt to new conditions; **responsiveness**, the ability of the system to self-heal or automatically respond to disruption; and **redundancy**, the characteristic of the system to have multiple pathways to achieve the mission (Anderson et al. 2019). Other approaches to defining energy resilience focus on the concepts of availability, accessibility, affordability, and acceptability (Laine 2017). Key resilience attributes used in this paper, and their relationship to reliability, are shown in Figure 2.

Figure 2. Attributes of resilience and their relationship to the notion of reliability

A **reliable** system is one that performs effectively under typical conditions. It is based on common methods of construction and will continue to work in most cases. Reliable systems are well maintained and monitored. The older the infrastructure, the less reliable it tends to be. Reliability forms the base of a resilient system.

Resilience can be thought of as how a system performs under duress. Does the system still supply necessary services in the case of an unforeseen event? Resilience is difficult to develop and maintain because the disruption is usually not specifically predicted. System redundancy and resourcefulness (flexibility) enable resilience in the face of unknown disruptions. Recoverability is the final piece of resilience. In the event of a system failure, how well and fast the system recovers to its pre-disruption state is an important facet of system resilience. Duration of a disruptive event is also informative to consider in terms of system design and the length of time over which a system will need to be operational, as a grid-connected or islanded system.

In this paper, energy resilience is approached from two angles. The first is related to the energy system components, and asks an engineering question: How well can the given energy system recover from disruptions? The second is related to the community needs that the energy system supports, and asks the socio-economic question: How well can the community recover from disruptions to the energy system?

1.3.1 Energy Resilience

There has been much attention to the resilience of the electric grid, as defined by the Federal Energy Regulatory Commission as its ability to "anticipate, absorb, adapt to, and/or rapidly recover" from disruptions (FERC 2018). Electricity system resilience focuses on preventing power disruption and, when an outage does occur, restoring electricity supply as quickly as possible, while mitigating the consequences of the outage (Anderson et al. 2017).

Reliable energy systems are key to keeping remote communities functional. Diesel generators are considered a **reliable** part of Arctic energy infrastructure (de Witt, Stefánsson, and Valfells 2019). There are often **redundant** generators available on-site to aid in resilience. However, the sole reliance on diesel for those generators can be a big stumbling block. Most remote communities have enough diesel storage on-site for at least a year, but if weather interferes with the supply lines, diesel can run out before the next delivery. Aging energy systems lower the reliability of diesel generators, and often the diesel technician and the replacement parts are not located near enough to provide for quick **recovery**. Remote Arctic communities survive frequent energy outages through their **resourcefulness.**

Establishing methods and metrics for quantifying or valuing energy resilience is an active area of research. Qualitative metrics based on attributes of resilience such as the four listed above will be used in this paper and are described in more detail in Sections 3–5. Quantitative metrics, such as cost-based metrics for electrical energy resilience (e.g., cost of an outage and other costs related to impacts of disruptions), and other quantifiable non-monetary metrics (e.g., days of survivability, number of affected facilities) are also being developed by research groups at NREL and other institutions (Hotchkiss et al. 2020). Those are meant for the scale of an individual energy system (e.g., a given electrical grid), so they cannot be calculated at the scale of this paper. Nonetheless, they help to frame some of the important questions around energy resilience in Arctic countries, such as survivability of outages.

1.3.2. Resilience of Microgrids and Distributed Energy Resources

Energy resilience metrics that apply to utility-scale electrical grids are not always applicable to microgrids and distributed energy resources (DERs). Anderson et al. (2017) proposed a methodology to quantify the economic and resilience benefits of hybrid renewable energy-storage-diesel microgrids, with resilience quantified in terms of the amount of time that the microgrid can sustain the critical load during a grid outage. By that metric, hybrid diesel-renewable-energy microgrid systems were found more resilient than diesel alone due to reductions in the run-time of the diesel generator. Other studies have found that growth in DERs serving electrical grids has boosted grid resilience in many cases (Zitelman 2020). DERs are resources sited close to customers on the distribution grid and include such technologies as solar photovoltaic, wind, geothermal, combined heat and power (CHP), energy storage, demand response, electric vehicles, microgrids, and energy efficiency (NARUC 2016).

DERs provide grid-related energy resilience components such as dispatchability (response with little or no notice); islanding capability (critical loads management during outages); geographic benefits such as siting at critical loads/locations; decentralization of the energy source; and flexible operations (NARUC 2020). To understand whether DERs hold up better than other options under natural disasters, the EPA compared six DERs to a “standby generator” option. The study—which notably did not include geothermal energy as a DER source—found that renewable DERs had a lower or equal likelihood of experiencing: (1) a fuel supply interruption; (2) damage to equipment; (3) performance limitations; and (4) a planned or forced shutdown during disaster events such as flooding, earthquakes, wildfires, and snow/ice than a standby generator. In the case of high winds and extreme temperatures, on the other hand, DERs performed worse than a standby generator (Naik-Dhungel 2021).

Taken together, these two studies suggest that renewable-energy-powered microgrids may be a resilient option for remote communities. However, limited deployment of geothermal microgrids in off-grid settings means that many unknowns remain about their performance.

1.3.3. Energy Resilience Beyond Electricity

While resilience metrics for electrical energy are a good starting point for this study, they are not adequate for an integrated evaluation of energy resilience in Arctic countries. Heat energy, for example, is a matter of survival in many Arctic and subarctic communities. Additionally, reliance on imported food means that food security is inextricably linked to energy for transport, storage, and distribution of imported food supplies. Hence, energy systems and food security cannot be viewed as separate issues. For example, utility outages, shipping delays, and subsequent impacts on the economy result in major disturbances to energy, water, and food systems in island settings (Daw and Stout 2019). Like island nations, remote communities in the Arctic are increasingly limited in local food resources, and their resilience depends on the adoption of integrated strategies that promote energy, water, and food security. When supply chains or transmission lines are compromised, a break-down in food security ensues.

Another linkage between energy resilience and food security is cold storage. Without electrical power, residents of remote communities in Arctic countries would not be able to power the freezers that store their subsistence or imported foods (Schaeffer 2018). The NunatuKavut Inuit who live in diesel-dependent communities in Canada place value on the socio-economic contributions of diesel-generation such as employment, reliability, familiarity, and contributions to community resilience—while also expressing concern about environmental degradation and the risk of fuel spills. Primary energy-system concerns relate to heat insecurity and dependence on external control, support, and imports (Mercer 2020).

These and other resilience-related factors, which are not accounted for in cost-based models, are called “externalities” because they are external to model calculations. Beyond **energy security, food security, ecological health, and economic development opportunities** discussed above, other externalities that are relevant in Arctic energy systems include **job security, energy equity, environmental justice, and climate justice**. While the value of externalities such as these are not included in economic analyses, they nonetheless play into investment decisions. Their value is often emphasized when communities are involved in the decision-making process. An integrated energy systems approach to Arctic energy includes careful consideration of resilience-related externalities.

1.4 Reframing Heat and Power Systems as Integrated Energy Systems

The Arctic Laboratory Partnership, consisting of five national laboratories, two Alaskan research institutions, and other institutions, held a series of workshops in 2020 to identify actionable pathways for R&D efforts that address important Arctic challenges. The following four cross-cutting themes emerged during the workshops:

1. Arctic energy in transition
2. Necessity of systems approach
3. Persistent and timely domain awareness
4. Tracking and predicting disruptive and abrupt transitions.

The first two themes—Arctic energy in transition and the necessity of a systems approach—echo Indigenous perspectives on resilience challenges in Arctic countries, which also emphasize transitions and integrated approaches:

> “As stewards of our lands and waters we have developed inextricable connections that form the foundation of our own understandings of our environments… our knowledges have been passed down from generation to generation, and are continually updated, adapted, and reshaped as our individual and collective experiences and observations inform them. Furthermore, our view of the ‘ecosystem’ is holistic and recognizes different systems, and the connections between them… our view includes humans as part of [a] highly interconnected system.”
>
> *Letter from Tribes and Tribal Organizations in Western Alaska to the National Science Foundation (Bahnke et al. 2020)*

In this paper, resilience is considered as an attribute of an integrated energy system (heat and power). This is a challenge, because: (1) available methodologies for evaluating energy resilience consider heat and power as separate individual components, and (2) thermal and electrical energy resilience is almost always evaluated at the scale of an individual building, or an individual grid, and not at the transnational scale of this paper. For this reason, elements were selected from several methodologies and approaches to resilience in this paper.

2 Current Energy Use in Arctic Countries

> "Energy systems of the north involve a diverse cross-section of resources, with widespread reliance on fossil fuels of various types (e.g., natural gas, diesel, coal) and a growing amount of renewable energy (wind, solar, geothermal, hydroelectric). Community power levels can range from as little as 35 kW to more than 10 MW. Heat is often the largest type of energy used in residential settings. Remote arctic communities typically experience high energy costs—in some cases exceeding $1 USD per kWh for electricity and $10 USD per gallon of heating fuel, with the result that residents can face energy bills that are over half their disposable income."
>
> *Factsheet on Energy in the Arctic, U.S. Department of Energy's Arctic Energy Office*

The eight Arctic countries contain two distinct groups based on energy characteristics. The first group includes systems in Europe—Finland, Norway, Sweden, Iceland; also called the "Nordic" countries—which are heavily **grid-connected**. The three Scandinavian countries (Finland, Norway, Sweden) have very clear legislation on energy security, and their energy industries are well regulated. Supply and demand define the price of electricity in the virtual electricity market called Nord Pool, through which electricity is bought and sold internationally among Nordic and Baltic states. The energy flows of oil, gas, coal, and uranium are linked to foreign actors and markets through Nord Pool, and regulated by the European Union as well as national energy policy. Most imported energy comes from Russia (Mortensen, Hansen, and Shestakov 2017). Iceland's national energy grid, on the other hand, is almost completely supplied by renewable energy sources.

The second group includes the United States, Canada, Russia, and Greenland. Some of those large-land-mass Arctic nations have grid-connected energy systems in their more densely populated southern parts, but are also defined by the **prevalence of remote microgrids**, typically supplied by diesel generation, which service remote subarctic and Arctic communities. In Canada for example, 190 out of 259 off-grid communities are exclusively dependent on diesel fuel for electricity generation (Mercer et al. 2020).

In Arctic countries, heat is a basic human need. Heating systems in grid-connected communities can be decentralized and based on natural gas or electricity. However, many grid-connected communities use centralized district heating systems, often co-generated with power plants fired by renewable energy sources or fossil fuels (Patronen, Kaura, and Torvestad 2017). These combined systems are energy efficient, reliable, and provide flexibility in their ability to cater to energy demand. For remote communities, heat and power generation is generally decoupled, but both are typically reliant on diesel fuel. In Alaska, for example, 69% of residential energy use is space heating (Alaska Housing Finance Corporation 2018).

2.1 Grid-Connected Integrated Energy Systems in Arctic Countries

An integrated view of energy systems for grid-connected communities in Arctic Countries includes the flow of both heat and electrical energy. It considers supply (raw energy inputs), conversion, transmission, distribution, and consumption (Patronen, Kaura, and Torvestad 2017). Energy sources for heat and power vary across grid-connected communities in the Arctic nations. The Scandinavian electrical grids are reliant on hydropower. Norway's grid has more than 900 hydropower plants, which provide 96% of the country's electricity, and is very resilient by most measures. Norway sells surplus power to nearby European nations, with planned expansions over the next two years into Germany and the U.K. via large undersea electrical cables (REVE 2020). Sweden and Finland supplement hydropower sources with nuclear energy sources, coal, and wind (Grahn 2019). Electrical grids in Canada also use hydropower extensively, as well as nuclear energy sources and coal (NRCAN 2021a, 2021b). Russia and the United States, including the Railbelt region of Alaska, use mostly natural gas for power although both use nuclear, coal, and hydro depending on the region (EIA 2021a, 2021c; Alaska Energy Wiki 2009). Greenland's electricity production is mostly from five hydropower plants supplying the power to six cities, and the rest is sourced from fossil fuels (Mortensen, Hansen, and Shestakov 2017). Other renewable energy sources such as geothermal, solar, wind, and biomass provide power to the grid for Arctic countries (Patronen, Kaura, and Torvestad 2017; Mortensen, Hansen, and Shestakov 2017). Iceland is the exception, with 99.9% of electrical generation stemming from renewable energy sources. Geothermal power plants in Iceland are generally run as baseload, while hydroelectricity plants handle fluctuations in grid load (Hardarson et al. 2018).

Correspondingly, the type of heating system also varies across grid-connected communities in the Arctic nations. Russia and the Scandinavian nations more consistently utilize district heating systems. Energy sources for district heating systems are natural gas in Russia and renewable sources in Scandinavia, particularly biomass (Patronen, Kaura, and Torvestad 2017; Hodgson 2009). Norway uses a high percentage of energy from waste incineration while Sweden and Finland use ground-source heat pumps (GSHPs), and in Finland coal is used for 25% of district heating (in southern Finland, 50% of district heating systems are coal-fired). In Iceland, houses are mostly heated with renewable energy, especially by direct geothermal heat (Patronen, Kaura, and Torvestad 2017). In areas of Canada and Alaska not connected to natural gas pipelines, diesel, fuel oil, and propane are used to heat homes (EIA 2021b; Furnace Prices Canada 2021). Some communities in remote parts of Canada use biomass for heating, especially in the Yukon Territories (Mortensen, Hansen, and Shestakov 2017). In Greenland, 16 towns have district heating systems that are sourced principally from waste heat recycled from diesel or biomass fired electricity generation, but can also be sourced from hydropower or oil-boilers. Despite this use of renewable energy, fossil fuels account for 70% of national heating needs as of 2015 because many residences are not connected to the main heating system and instead use private oil-fired installations (Naalakkersuisut 2018).

Russia is highly dependent on district heating systems that are a remnant of the Soviet era and have not been renovated since its collapse in the 1990s (Hodgson 2009; Sorokina 2019). While the oldest district heating system located in Russia was installed over 100 years ago, centralized heat and power became available in residential homes starting in 1924 (Hodgson 2009; Sorokina 2019). The power source for heating depends on the region—plants connected to Unified Electric Grid are mostly powered by natural gas, while coal-fired plants are common in Siberia and the Far East (Hodgson 2009). Co-generation plants and heat-only boilers deliver hot water to homes through pipes that have long exceeded lifetime expectations, a highly inefficient system prone to leakage with heat loss up to 40%–50% (Sorokina 2019).

2.2 Combined Heat and Power (CHP) and Co-Generation

CHP, also referred to as co-generation, is the simultaneous production of electrical and thermal energy from a single fuel using an electricity generator and a heat recovery system. The thermal energy can be used in heating or cooling applications (Strickland and Nyboer 2002). Repurposing waste heat rejected from one process to another process results in gains in energy efficiency and reduced GHG emissions. CHP is increasingly used in district energy systems worldwide (e.g., urban settings, campuses, military bases) and in industrial applications to gain efficiency and achieve decarbonization goals. More than 30% of electricity production in Finland, Denmark, and the Netherlands is associated with CHP (Strickland and Nyboer 2002).

2.3 Remote/Isolated Integrated Energy Systems in Arctic Countries

Figure 3 shows the supply, storage, and distribution of energy—almost always diesel fuel—to remote Arctic communities typical in Canada, Russia, the United States (Alaska), and Greenland. These communities are highly dependent on this resource for heat and power usage (Allen et al. 2016; Knowles 2016; Sokolnikova et al. 2020; Lovekin et al. 2016). While many remote communities own and operate their own diesel gensets, some remote communities receive electrical power from a transmission lines from larger towns and cities.

Microgrids serving remote communities in Arctic countries can be stand-alone systems that meet the needs of one specific site, or that serve multiple intertied locations (Arctic Energy Office [AEO] 2020). Typical microgrids produce <5 megawatts of electricity (MWe) and are supplied by one or more energy sources, most commonly diesel fuel. Renewable energy sources can be used in microgrids but are often integrated with fossil energy sources. Consumers include residential, commercial, and community loads, which vary in size throughout the day and the year. A transmission and distribution network connects the energy source, or sources, with the energy users; a control system manages the generation (and sometimes the loads) and often uses one or more types of energy storage (e.g., batteries, flywheels, hot water tanks) to buffer differences between the supply and demand, and to enhance overall system efficiency (AEO 2020). Rare villages in Arctic countries proximal to oil and gas fields use natural gas, such as Utqiaġvik and Nuquisit close to the North Slope of Alaska (Fay et al. 2013; EPA 2020).

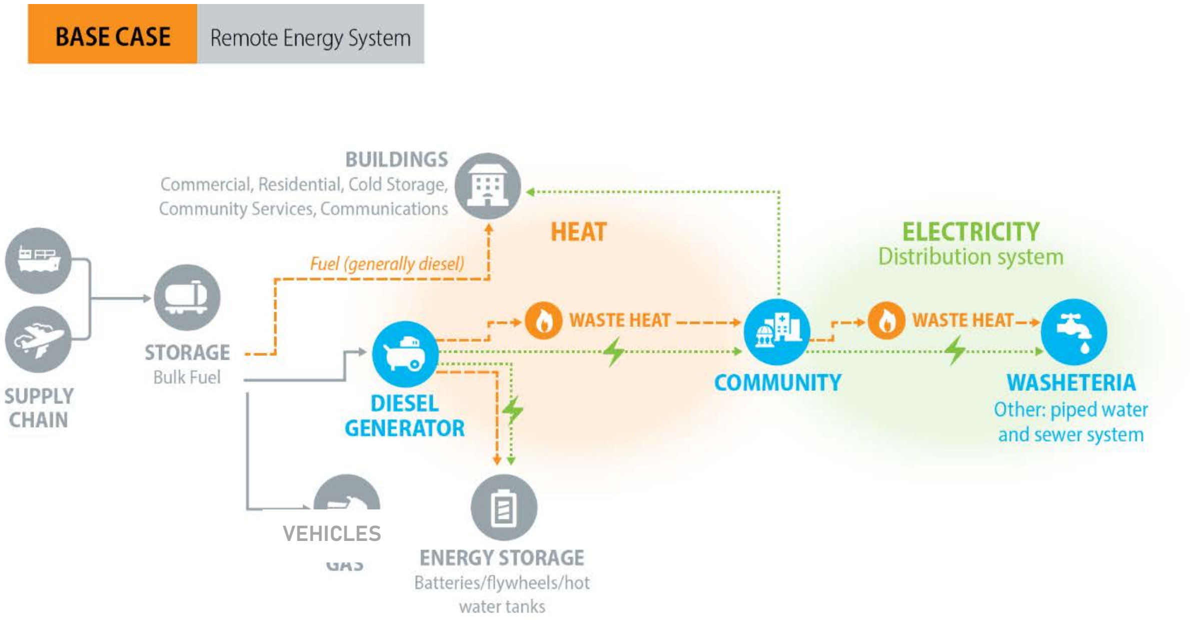


Figure 3. Schematic flow diagram for a generalized remote energy system in an Arctic country

Bulk fuel is generally barged in to remote communities, stored in large tanks on-site, and distributed to the community for residential heating, vehicle use, and one or more diesel generator(s) (Kohler and Schutt 2012; Miner et al. 2015). Heating can be supplemented with wood-burning stoves. Generated electricity (and waste heat in some cases) powers buildings including the washeteria, which is a central watering point common in rural Alaska providing laundering and showering needs as well as treated water for the community (Alaska Native Tribal Health Consortium 2015; EIA 2021a). With this set-up, villagers need to haul their waste to a sewage disposal site themselves, although some rural areas have a piped water system that delivers from a centralized source to homes or use trucked water distribution and sewage collection systems (Bressler and Hennessy 2018; Mosites et al. 2020). Many remote communities in Alaska, Canada, Russia, and Greenland do not have washeterias, and lack water and sanitation services. Unserved regions of Greenland and Alaska use what are known internationally as “honey buckets” for raw sewage. They obtain water from local rivers/streams, wells, snow melt-off, rain catchment, winter ice from surface ponds, and other sources with or without water treatment systems (Daley et al. 2018; Hickel et al. 2018; Schaeffer et al. 2018).

2.4 Cost of Power and Heat in Arctic Countries

The cost of power and heat is highly variable in Arctic countries (Table 1). All costs in this paper are reported as U.S. cents per kilowatt hour (¢/kWh) unless indicated otherwise. The majority of remote communities in Russia, Canada, Greenland, and the United States (Alaska) are extremely dependent on diesel, resulting in disproportionately high costs for heat and power compared to the centralized grid (Holdmann and Asmus 2019; AEO 2020). To aid communities in Arctic countries struggling with high fuel costs, national, state, and local governments sometimes provide financial assistance to communities for both heat and power (Izhbuldin and Dobrovolskaya 2019; Lovekin et al. 2016; Poelzer et al. 2016). This financial assistance can include direct subsidies as well as assistance for fuel transport and storage, which decrease costs of electricity generation averaging 65¢/kWh in Arctic countries (Chade et al. 2015; Poelzer et al. 2016). Heating fuel costs are subsidized in remote communities in Alaska, as well as Greenland, Russia, and some communities in Canada such as Nunavik, from 22.8 to 18.3 U.S. ¢/kWh (Table 1).

Table 1. Average Cost of Power and Heat (2011–2020) in Arctic Countries, in USD¢/kWh for Residential, Commercial, and Industrial Customers. Data Shown for Grid-Connected and Remote Communities (Subsidized and Unsubsidized Costs).

Data sources: Energy Information Administration (EIA) (2021a-d), Global Petrol Prices (2020), Statista (2016, 2021), Richter (2011), International Renewable Energy Agency (IRENA) (2017), Thayer (2019), Poelzer et al. (2016), Lovekin et al. (2016), and Kekelidze et al. (2019).

Country	Grid-Connected Cost of Power			Remote Cost of Power		Grid-Connected Cost of Heat			Remote Cost of Heat	
	Residential	Commercial	Industrial	Subsidized	Unsubsidized	Res.	Comm.	Ind.	Subs.	Unsub.
U.S. (AK)	13.0	10.7	6.9	24.3	46.2	3.5	2.6	2.0	11.5	
Russia	6.0	8.3	6.5	2.9–6.3	150.0	1.1		0.5		
Iceland	13.4	4.8	4.3							
Greenland	26.4			52.7		12.5			11.5	
Canada	11.0	8.8	8.9	17–42.0	114.0	2.6	2.7	1.0	15.2	18.9
Norway	32.5	5.0	10.0							
Sweden	22.0		8.9							
Finland	21.0	12.0	8.6							

Alaska

In Alaska, rural communities face electricity costs that are three to five times higher than the rest of the state, despite lower consumption and income per capita than residents living on the regional grid (Brinkman et al. 2014; Fay, Meléndez, and West 2013; Thayer 2019). Alaska's Power Cost Equalization (PCE) program subsidizes cost of electricity for the first 500 kWh/month, although at a relatively high price for consumers compared to energy prices in other remote communities (Fay, Meléndez, and West 2013; Holdmann and Asmus 2019). The PCE endowment draws funds from the Constitutional Budget Reserve and from the National Petroleum Reserve-Alaska (Alaska Energy Authority 2019). Its budget is therefore variable and linked to petroleum revenues. In February 2021, the PCE endowment had a market value of $1.13 billion (Alaska Energy Authority 2019; Alaska Department of Revenue 2021). In 2019, the weighted average residential rate before PCE was 46¢/kWh, whereas the PCE reduced the cost to 24¢/kWh (Thayer 2019; Table 1). Heating is likewise sourced by diesel and is the most expensive residential utility in rural Alaska (Fay, Meléndez, and West 2013; Thayer 2019).

Canada

The Canadian federal and provincial/territorial government as well as some utility companies provide subsidies for remote communities varying per territory, offsetting the cost of diesel fuel and generation (Lovekin et al. 2016). For example, Nunavat Electricity Subsidy Program brings the price of the first 700 kWh of electricity to a flat rate of 30.15¢/kWh since the cost of power is one of the highest in remote Canada, ranging from 60–114¢/kWh (Touchette et al. 2017).

Russia

In remote Russia, diesel fuel is subsidized mainly due to high costs of transport (Kekelidze et al. 2019). Residents pay lower costs for energy than other consumers and large-scale utilities due to cross-subsidies between these companies and the state, resulting in heat and power prices that are artificially reduced (Holdmann and Asmus 2019; Izhbuldin and Dobrovolskaya 2019; Kekelidze et al. 2019). The range of prices in Table 1 is based on remote communities in Krasnodar Krai, Bashkortostan, Altai Republic, Yakutia, and Kamchatka with no differentiation between day and nighttime voltage (Kekelidze et al. 2019).

Greenland

Greenland's minimum and maximum prices for electricity as well as uniform prices for heating are determined by Nukissiorfiit, a utility supplying most of Greenland's energy, and cross-subsidized within Nukissiorfiit and by the government. Towns and villages supplied by hydroelectricity generally pay the minimum price for electricity and here are classified as grid-connected, while those supplied by diesel-generated power usually pay the maximum price and here are classified as remote. Meanwhile, the fishing industry pays 41.5% of the local applicable price for electricity (Naalakkersuisut 2018). Fixed and interruptible heating can both be electric or water-based; however, interruptible heating is slightly less expensive because it generally requires backup and here is classified as remote (Naalakkersuisut 2018; Table 1).

Nordic Countries

The grid-connected Nordic countries have relatively high residential electricity prices, up to six times higher than the price of commercial electricity in the case of Norway (Table 1). However, the prices of electricity to commercial and industrial consumers in Nordic countries is only slightly higher than those of the rest of the Arctic countries.

Nordic countries are reliant on centralized heat and power, and commonly use district heating systems to provide hot water and heating for homes (Lund and Toth 2021; Figure 4). In Iceland, geothermal heat accounts for lower prices (Richter 2016). Flatey and Grimsey Island, however, are the only two remote communities in the country that are dependent on diesel for energy, and Grimsey Island is responsible for 75% of energy subsidies by the Icelandic government (DiBari 2019).

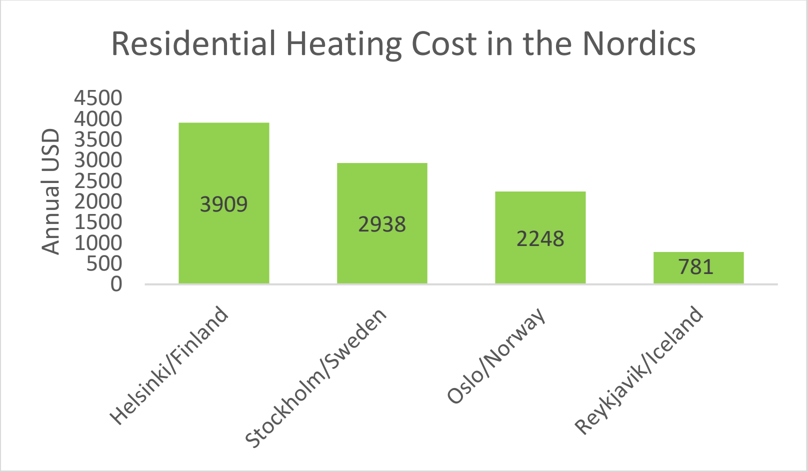


Figure 4. Cost of heat (hot water and space heating), in annual USD, per residence in major cities in the four Nordic countries

Source: Richter (2016)

Costs of Geothermal Power and Heat in Arctic Countries

The prices of geothermally generated electricity in Arctic countries can be difficult to quantify. Prices for geothermal power in Iceland are linked to hydroelectric. Those prices were 13¢/kWh in 2020. Prices for geothermal power in Kamchatka, Russia, were 41¢/kWh in 2018 (Kekelidze et al. 2019) while the most recent prices published for geothermal power at Chena Hot Springs in Alaska were 5¢/kWh in 2006 (Holdmann 2007).

2.5 Threats and Vulnerabilities in Integrated Energy Systems in Arctic Countries

The USAID-NREL Partnership's Resilient Energy Platform published the *Power Sector Resilience Planning Guidebook* (Stout et al. 2019), which presents a methodology involving the identification of natural, technological, and human-caused **threats**, with each threat assigned a likelihood score from 1 (low) to 9 (high). The impacts of the threats are then defined for the power sector and the end user. Based on identified threats, the method then assesses system **vulnerabilities**, assigning a severity score from 1 (low) to 9 (high). Risks are calculated by creating a matrix of threats and vulnerabilities to determine which threats influence each vulnerability. This approach is designed for community-scale analysis, so it cannot be employed at the scale of this paper, but aspects are borrowed from this approach to outline general threats facing Arctic countries, and associated vulnerabilities.

Natural events such as severe weather threaten diesel supply lines to remote communities. Technological issues associated with aging technology and lack of a local trained workforce are large threats in microgrid communities. The impact of natural and technological threats facing remote communities is geospatially limited to the community due to the distributed nature of the systems. For example, if a single diesel generator fails, the effects are usually limited to a single community, as there is often not an integrated system. On a community scale, a single generator failure can be catastrophic if not brought back online quickly. Because remote communities in the United States, Canada, and Russia are highly dependent on diesel for both heating and electricity, a diesel shortage caused by natural threats would have severe impacts for the end user. Human-caused threats are less likely to occur in remote communities, because decentralized systems are less likely to be the targets of terrorism or cyberattacks. Any accidents caused by humans (e.g., cutting an underground line during construction) will have localized impacts.

For a grid-connected system, the likelihood of natural threats is higher due to the larger footprint of the area connected by the grid. While some large power grids are not dependent on a single energy source (decreasing the likelihood of a fuel shortage caused by natural threats), others are dependent, particularly in the hydropower-heavy countries like Canada, Iceland, and Norway. On the other hand, grid-connected systems have more infrastructure, making them more susceptible to failures of systems and human-caused threats such as accidental cutting of lines. For grid-connected communities in Scandinavia and Iceland, natural threats may have impacts such as power outages. Outages may also be caused by technological and human-caused threats such as infrastructure and system failures.

The simplified energy supply chain includes transportation, storage, distribution, conversion, combustion, transmission, and consumption. Each of the links in the supply chain encompasses one or more major vulnerabilities. For example, electricity transmission is a system vulnerability because some of the more remote transmission lines show evidence for major energy loss, but funding to repair remote transmission lines is difficult to secure. At times, local village corporations fund upgrades themselves (Schaeffer et al. 2018). Transportation is another example: often fuel delivery is only possible on a seasonal basis, for example by barge while the ocean and rivers are free of ice, or by tanker truck during only the very coldest months when ice roads can be constructed and used. In some cases, it must be flown in (AEO 2020).

A key vulnerability of integrated energy systems in Arctic countries is the life-or-death requirement of enough heat during the cold winter. In Scandinavian countries, district heating systems are linked to electrical power grids, requiring a given energy system to ensure that there is enough electrical power in the power grid during the cold winter. During the coldest time of the year in Finland, for example, peak heating demand during winter cannot be met by domestic production capacity, and thus imports are needed (Laine 2017).

Based on the above brief evaluation of threats to energy systems in Arctic countries and associated vulnerabilities, it appears that business-as-usual is weakening the resilience of affected communities. The following sections review methods and metrics for measuring resilience at the international scale of this study and apply pertinent resilience metrics to an alternative case: an integrated energy system supplied by geothermal energy.

3 Resilience of Integrated Energy Systems

3.1 Measuring Resilience of Integrated Heat and Power Systems

Existing literature on resilience of energy systems is relatively sparse and ranges from high-level thought pieces on how to think about resilience to slightly more in-depth coverage proposing limited metrics by which one might be able to compare relative resilience of energy systems. A comprehensive, widely accepted understanding of how to measure or quantify resilience does not yet exist. There is no "one-size-fits-all" approach to resilience because solutions will need to be place-based and culturally appropriate to address risks (e.g., hazards, threats, and vulnerabilities) and their associated consequences, at the local level. Every system and every community is subject to its own set of unique risks based on the local geographic, climatic, political, social, and economic context. Therefore, resilience is best understood as a comparative exercise—a particular system may be considered relatively more or less resilient than another proposed or alternative system based on a range of mostly qualitative and often subjective criteria. However, that does not mean that trying to evaluate resilience is a futile exercise. On the contrary, there are a variety of relative resilience criteria that can be evaluated to allow more structured analysis of resilience improvements associated with a particular resilience mitigation strategy, which are detailed next for both electric and thermal systems.

3.1.1. Measuring Resilience of Electrical Grids

Power sector resilience incorporates a transparent and adaptable process that can be used to guide power sector stakeholders to understand risks and mitigate those risks through resilient solutions (Stout et al. 2019; Hotchkiss and Dane 2019). As mentioned in Section 2.1, the method outlines key steps, including:

1. Identifying the main threats to a particular system (e.g., natural threats, technologic threats such as equipment failure, and human threats such as accidents and intentional acts)
2. Estimating the consequences of identified threats (e.g., effects on ability to deliver power, effects on operating costs or additional capital expenditure, effects on human health and safety)
3. Assessing the vulnerabilities of the existing or proposed/alternative system (usually either vulnerabilities in infrastructure/hardware or to processes/operations)

Through each of these steps, a qualitative thought exercise can be used to determine the relative severity of these threats, impacts, and vulnerabilities for the community under consideration. The threats to, and vulnerabilities of, a system can be linked with one another via a matrix approach that allows rough visual comparison.

Although there are no established quantitative metrics for power system resilience, there are proposed metrics that could be used to value and/or quantify resilience for a particular system. In isolated grid settings (i.e., microgrids), the relative number of days that a particular system could survive a disruption without significant loss of service is one possible metric (Anderson et al. 2017). Other metrics focus on valuing the benefit of resilience improvements by looking at costs associated with loss of service (i.e., value of lost load). In any case, these resilience metrics are still used primarily to establish a performance baseline that can then be used to evaluate the relative additional resilience benefit of proposed improvements/mitigation measures against that baseline, such as evaluating the benefits of adding solar photovoltaics and/or batteries to a diesel microgrid (Anderson et al. 2019).

Others look at relative system stability and response rate as a key resilience metric. Particularly in remote/isolated grid settings, a power system must be able to deliver a stable, safe, and reliable power supply under the full range of anticipated operating conditions before any considerations of resilience can be made. Considering how well a system meets these same power stability and quality criteria under the most extreme conditions or during shocks and other disruptions to the system can then provide insight into the potential resilience of the system, at least from the perspective of continuation of usable power service. Booth et al. (2020) clearly outlined a handful of basic power system requirements for isolated power systems, including redundancy (i.e., is there enough dispatchable generation available to not only meet load but also ensure continued power supply in the event a generating source is lost), in-rush currents, reactive power, availability of contingency for load growth, harmonic distortion handling, and transitioning during disruption. Beyond these basic power system engineering requirements, the ability of a generator to operate flexibly and provide necessary ancillary services such as up-regulation, and spinning reserves can contribute to the resilience of a system by providing flexibility (Edmunds et al. 2014). The ability of a generator to support a grid coming back online after a blackout, called “black start,” is another important feature.

Distilling these lessons down, a picture can be painted of the critical power system components that should be examined and key questions that should be asked when evaluating the resilience of a particular power system, which are aligned with the previously identified resilience attributes (reliability, redundancy, resourcefulness, and response). Furthermore, responses have been split into two discrete subcategories: recovery (i.e., how well can the system recover from a disruption) and operations (i.e., how well can the system function to maintain fundamental service during a disruption). These resilience attributes, system components, and criteria are presented in Table 2. We revisit this table in Section 6 and consider these criteria in the context of several case studies of geothermal systems.

Table 2. Key Power System Resilience Attributes, Components, and Criteria

Attribute	Component	Criteria
Reliability: How does it perform in typical conditions?	Wellfield	How reliable is the wellfield? How does it respond to shocks?
	Generation equipment	How well does the generation equipment stand up to regular use? How does it respond to shocks?
	Balance of system equipment	How well do components that make up the balance of system (housing, racking, inverters, poles, etc.) stand up during regular and extreme conditions?
	Low-load operation	How well does the system operate under low-load conditions? Does it lose efficiency?
Redundancy: Are there single points of failure?	Fuel storage	Is there on-site fuel storage? How much? How vulnerable is stored fuel?
	Number of generators	Are there multiple generation sources in the event of an outage?
Resourcefulness: How are the needed resources utilized?	Critical transportation routes for fuel and supplies	What transportation logistics/transportation infrastructure is required (e.g., for fuel/parts supplies)? How vulnerable are these logistics chains?
	Power sector workforce	What kind of skilled labor is required? Is there a local workforce available on-site?
	Variation in resource	How variable is the resource? Is it dispatchable to meet need flexibly? Can it be easily forecast?
	Infrastructure needs	What other infrastructure is required to build, operate, and maintain the system?
Response (Recovery: can the system bounce back from disruption?)	Natural disasters (weather-related)	How susceptible is the system to weather-related disasters?
	Natural disasters (geologic hazards)	How susceptible is the system to geologic hazards?
	Response to variation in resource	How quickly can the system respond to variations in resource availability?
	Spare parts	How easily accessible are spare parts?
	Black start	Can the system support black start in case of a blackout?
Response (Operation: is the power system stable and able to provide ancillary services?)	Switching capability	Can the system easily switch generation sources in the event of a shock or disruption without significant loss of service?
	Ramp up/down	How quickly can the system ramp power production up or down to follow changes in load? Are there additional components required to make this possible?
	Reserve capacity/spinning reserve	What is the ability of the system to maintain unused reserve capacity in the event of sudden, large change in load or generation output?
	Inertial response	Can the system overcome transient imbalances between supply and demand without adversely affecting power quality?
	Frequency response	Does the system have the necessary control to maintain stable frequency in response to changes in load and/or output?
	Voltage response	Does the system have the necessary control to maintain stable voltage differential in response to changes in load and/or output?

3.1.2. Measuring Resilience of Thermal Systems

3.1.2.1. Buildings-Scale Heating/Cooling Systems

The term thermal resilience is used to evaluate building-scale resilience to heating (or cooling) outages. Thermal resilience is defined as how a building reacts to thermal stresses, both hot and cold. In the Arctic thermal resilience is determined by how the building reacts to lack of heat during the cold seasons. A thermally resilient building has a reliable and redundant heating system, a robust (resourceful) building envelope, and the ability to recover from a heat outage. The building envelope is the key component in determining the resilience of a building. A building with large thermal mass, high levels of insulation, and minimal air leakage will be more resilient because it can survive without active heating for longer than a building with a lesser envelope (Zhivov pending).

3.1.2.2. District Heating/Cooling Systems

The four resilience attributes of redundancy, resourcefulness, recovery, and reliability can be applied to district heating systems. Table 3 lists examples of specific attributes for a resilient district heating system that correspond to the four resilience characteristics. Some are more important than others; for example, building thermal resilience, meshed distribution systems, and redundant heating plants and sources are key components of a resilient district heating system. Meshed distribution systems allow for heat to be routed around a disruption in the delivery lines or pumps. When combined with multiple heating plants, meshed distribution can allow a system to function even with the complete failure of a heating plant. When varied heat sources are added the system becomes resilient to supply line disruptions as well.

Building-level thermal resilience is a particular part of resourcefulness in district heating systems. However, building-level thermal resilience is often outside the control of the district heating system management; managers and building owners need to work together to ensure this key component of the district heating system is addressed.

Table 3. Key Heating System Resilience Attributes and Components

After Anderson et al. 2017; Stout et al. 2019; and Hotchkiss and Dane 2019

Attribute	District Heating Components
Reliability: *Does it perform in typical conditions?*	Maintenance plans
	Performance monitoring
	Age of system/components
	Maintain outage stats
	Leakage detection system
Redundancy: *Are there single points of failure?*	Multiple heat plants
	Multiple heat sources
	Redundant workforce
	Redundant pumps
Resourcefulness: *Are there diverse and flexible options?*	Building-level thermal resilience
	Meshed distribution systems
	Ability to exceed design capacity in extreme cold events
	Thermal storage capacity
	Ability to meet multiple temperature delivery needs
	Time to recovery—thermal resilience of buildings in the system
	Ease of recovery—supply chain flexibility
Recovery: *Can system bounce back from disruption?*	Standardized parts and supplies
	Plan for recovery
	Spare parts inventory
	Workforce for recovery

3.2 Geothermal Resilience

> *"Geothermal is unlimited & does not suffer from market fluctuations like natural gas or fuel oil. It is the perfect tool for diversification & scalability as it provides stability in terms of price & supply. These features are key for driving the project to a national and/or international level."*
>
> *Icelandic Arctic Cooperation Network, 2020*

Geothermal energy serves as the baseload for many energy systems and can offset costs and emissions from diesel usage (Brophy, Lund, and Boyd 2015; Lund and Toth 2021). While use of geothermal energy reduces fossil fuel use, backup diesel generation is often involved to increase grid stability and resilience by providing a redundant source of power (Wender 2016). In some cases, diesel generation is coupled with geothermal energy, and can be integral to the formation of the grid. In Russia, the geothermal Pauzhetka power plant uses an additional four operating diesel generators to produce electricity (Svalova and Povarov 2020). The Chena Hot Springs geothermal microgrid in Alaska is actually a geothermal-diesel hybrid (Holdmann and Asmus 2019).

In Iceland, geothermal power plants are generally run as baseload, whereas hydropower plants handle fluctuations in grid load; however, recent experiences show that geothermal power plants can improve the stability and flexibility of Iceland's power system and complement the response of the hydropower plants. The turbine units have been implemented with functions that enable the units to contribute to the control of grid frequency and, in situations where the area is cut off from the main grid, to actively control the islanded grid frequency. Design of the plant aims to guarantee that steam supply and auxiliary systems have sufficient redundancy and capability to handle varied operational conditions. The plant has been provided with black-start capabilities to allow for energizing the power lines and transformers without any external power. Extensive tests have been done with the grid operator on the active grid to simulate the situations that can arise and monitor the response of the plant (Hardarson et al. 2018).

4. Geothermal Energy Use in Arctic Countries

4.1. Overview

The applications of geothermal energy fall into three distinct classes. The classes are based on approximate temperature of the geothermal resource used, and indicate the type of applications that can be achieved (after CanGEA 2016):

1. Geo-exchange, also known as geothermal heat pumps (GHP) (<30°C)
2. Direct use of geothermal heat (30°C–150°C)
3. Geothermal power (>80°C).

In Arctic countries, typical barriers to geothermal growth such as those outlined in *GeoVision* (2019) are compounded by a paucity of data on geothermal resource availability, higher capital costs of construction in Arctic countries, and even longer project timelines between project startup and operations (Islandsbanki 2011).

Table 4 summarizes the geothermal energy use in the eight Arctic countries. Three out of the eight Arctic countries have geothermal power plants: Iceland, the United States, and Russia. Though United States has the greatest installed geothermal capacity worldwide, only one plant is located in a subarctic climate (Alaska). Iceland has eight geothermal power plants (Huttrer 2020), and Russia has five geothermal power plants, all located on Russia's Kamchatka peninsula (Svalova and Povarov 2020; Figure 5).

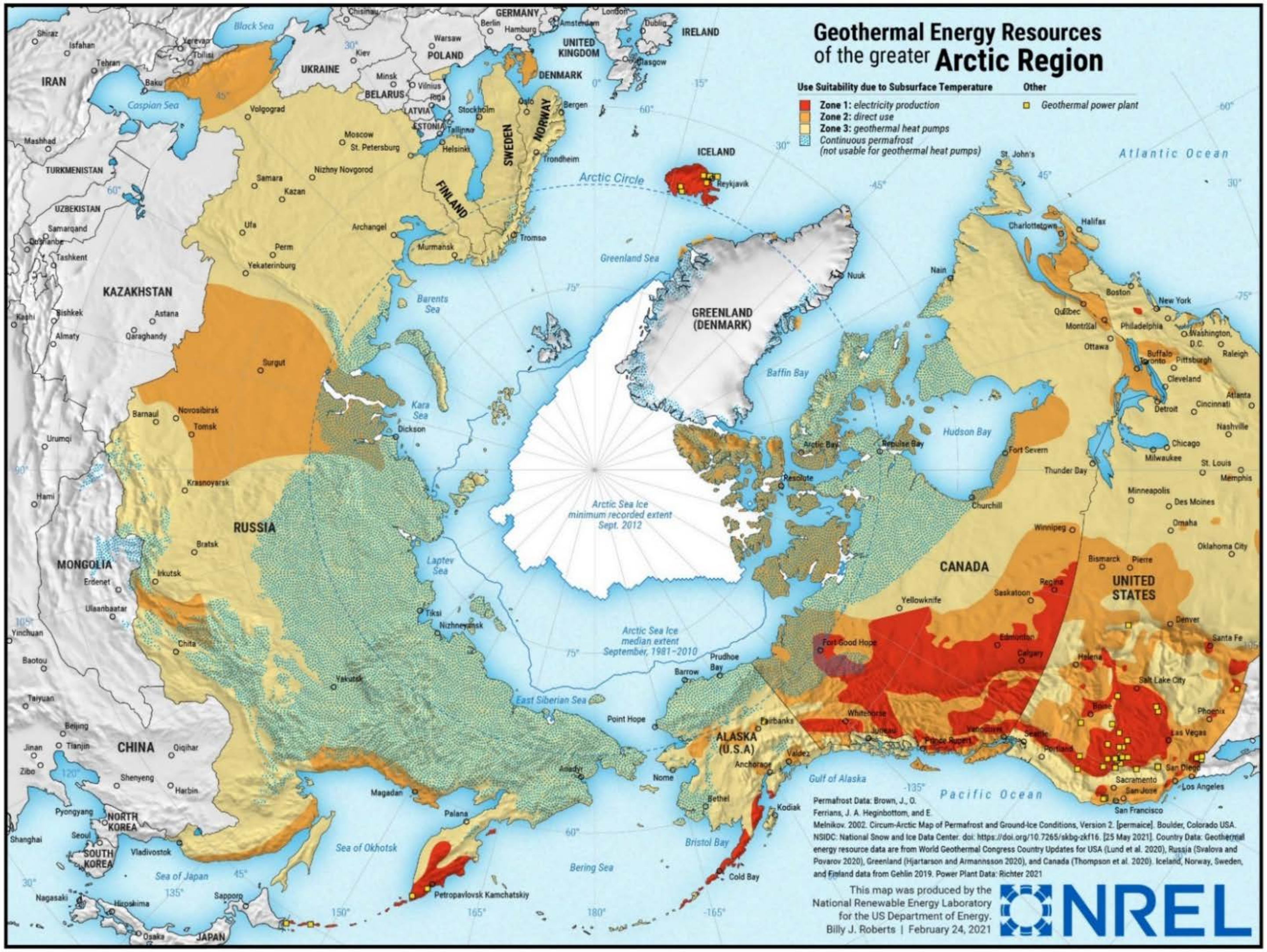
Table 4. Use of Geothermal Energy (Power, Direct Use, and GHP) in Arctic Countries

Note that very few of these systems are installed in Arctic or subarctic regions of the eight Arctic countries

Country	Number of Power Plants	Installed Capacity (MWe)	Number of Direct Use Systems	Installed Capacity (MWth)	Number of GHP Systems	Installed Capacity (MWth)
USA	99	3,700	469	482.63	1,685,800	20,230
Russia	5	82	No data	421	1,000	12
Iceland	8	755	No data	2,367	126	5.6
Greenland	0	0	1	0.1	0	0
Canada	0	0	13	8.78	103,523	1,822.5
Norway	0	0	1	0.18	60,000	1,150
Sweden	0	0	0	0	591,000	6,680
Finland	0	0	0	0	140,000	2,300
TOTALS	**112**	**4,537**	**484**	**3,280**	**2,581,449**	**32,200.1**

The availability of geothermal resources is understood in most of the Arctic countries, with the exception of Iceland. The general geothermal resource types available in each of the Arctic countries are shown in Figure 5, grouped by the type of applications that can be achieved (geothermal power, direct use of geothermal heat, and geo-exchange/GHPs). Baseline subsurface data for Figure 5 come from a wide variety of sources and vary in quality. Also shown on this map are the locations of geothermal power plants in the Arctic countries (data courtesy of Richter 2021).

The prices of geothermally generated electricity in Arctic countries can be difficult to quantify. Prices for geothermal power in Iceland are linked to hydroelectric, for example. Those prices were 13¢/kWh in 2020. Prices for geothermal power in Kamchatka, Russia, were 41¢/kWh in 2018 (Kekelidze et al. 2019), while the most recent prices published for geothermal power at Chena Hot Springs in Alaska were 5¢/kWh in 2006 (Holdmann 2007). This extremely wide range is due to a combination of technical, resource, and socio-political factors.



Permafrost Data: Brown, J., O. Ferrians, J. A. Heginbottom, and E. Melnikov. 2002. Circum-Arctic Map of Permafrost and Ground-Ice Conditions, Version 2. [permaice]. Boulder, Colorado USA. NSIDC: National Snow and Ice Data Center. doi: https://doi.org/10.7265/skbg-zkf16. [25 May 2021]. Country Data: Geothermal energy resource data are from World Geothermal Congress Country Updates for USA (Lund et al. 2020), Russia (Svalova and Povarov 2020), Greenland (Hjartarson and Armannsson 2020), and Canada (Thompson et al. 2020). Iceland, Norway, Sweden, and Finland data from Gehlin 2019. Power Plant Data: Richter 2021

This map was produced by the
National Renewable Energy Laboratory
for the US Department of Energy.
Billy J. Roberts | February 24, 2021

Figure 5. General geothermal energy resources by utilization type, and locations of geothermal power plants, in the eight Arctic countries

Map credit: Billy Roberts, NREL

4.2. Geo-Exchange (<30°C)

Geo-exchange, also known as geothermal or ground-source or geothermal heat pump (GHP) technology, is used in residential/commercial space heating and cooling applications with the use of a heat pump and tubing at shallow depths. The commonly encountered ~10°C temperature found in moderate climate shallow soil beneath a building (from a few meters to a few hundred meters below the surface) can be used to cool the building on a hot summer day and to preheat fresh air coming into the building on a winter day (CanGEA 2016). However, the suitability of these systems for cold and Arctic climates has not been proven. GHPs can function in areas of the Arctic that are free of continuous permafrost; however, there is limited research on their long-term performance (Meyer et al. 2011).

Sweden is a world leader in low-temperature geothermal applications, with more than 500,000 GHP systems installed for space heating and domestic hot water heating, and 6,680 MW of installed heating capacity (Gehlin, Andersson, and Rosberg 2020). There is a geothermal district heating network in the city of Lund, which has been producing heat since 1985 (Aldenius 2019). GHP technology is also widely used in other Scandinavian countries. In Finland, 140,000 systems have been installed and more than half of all new houses use GSHPs for heating and cooling (Kallio 2019). In Norway, 60,000 GHPs are installed, and 80% of heating demands are covered by direct electricity (from hydropower) or heat pumps (Midttømme et al. 2021). Sweden's higher usage of GHPs compared with neighboring countries can be explained by policy differences (Hirvonen 2017). Geo-exchange deployment in Arctic nations is provided in as installed capacity (MWth) and annual production (TJ/yr). Also noted is whether the GHP systems use thermal energy storage. Note that the majority of the GHP systems listed in Table 5 are not installed in subarctic parts of the countries, particularly in the United States.

4.3. Direct Use of Geothermal Heat (30°C–150°C)

Direct use of geothermal energy applies heat for purposes such as district and individual space heating and heating for greenhouses, soil, and pools (Rubio-Maya et al. 2015). Traditional and historic direct use of geothermal energy in Arctic countries is centered around health and medicinal uses, recreational bathing, and food production. The Iñupiaq people of western Alaska recount stories referring to hot springs sites as shamanistic training grounds (Hallbert 2013). One such site, Pilgrim Hot Springs in Western Alaska (also called the Kruzgamepa homestead) was selected for an orphanage to house the many native children who became homeless during the 1918 influenza epidemic. The buildings were geothermally heated (and had then-rare flush toilets), and geothermal greenhouses produced vegetables all year long (Bland 1972).

Most of the Arctic nations utilize geothermal energy for some form of heating. The United States, Russia, and Iceland use geothermal fluids for applications such as district and individual space heating, agricultural drying, and heating greenhouses, soils, and pools (Lund and Toth 2021). The breakdown of direct-use applications is shown in Table 5. Geothermal direct use is widely deployed in Iceland, with thousands of MWth of installed capacity, and is also widely used in the non-Arctic parts of the United States and Russia, with hundreds of MWth of installed capacity. Greenland has a geothermal spa, Canada has 13 geothermal hot spring resorts, and Norway uses geothermal heat for snow removal at the Oslo airport Gardermoen (Hjartarson and

Armannsson 2020; Midttã 2020; Thompson, Harmer, and Wainer 2020). Finland and Sweden have no operating geothermal power plants or ongoing applications of direct geothermal use.

Geothermal district heating (GDH) is used in many Arctic countries. GDH is a direct-use application where hot water is produced from geothermal fields and subsequently piped to community buildings, providing heating needs (Lund and Toth 2021). While district heating is used all around the world, it can be especially favorable in cold climates due to a higher load factor which can improve profitability and efficiency (Lund and Chiasson 2007; Lund and Toth 2021). GDH systems can work with high-enthalpy fluids such as those from the Svartsengi field in Iceland or low-enthalpy geothermal resources such as those used from Chena Hot Springs, Alaska (Ragnarsson et al. 2020). In the Arctic nations, GDH accounts for the following percentages of direct use: 70% in Iceland, 19% in the United States, and 26% in Russia (calculated from Lund and Toth 2021). The United States has 23 GDH systems (Robins, Kolker, and Espino 2021/in preparation) however, the majority of those are not installed in subarctic or Arctic regions. Iceland has about 30 different GDH systems in towns and villages and 200 smaller rural ones, and Russia has seven locations that have GDH applications (none of which are in the Arctic or subarctic) (Lund and Toth). Table 5 shows the types of geothermal direct use applications in Arctic countries.

Table 5. Breakdown of Geothermal Direct Use Applications (Other Than Heat Pumps) in Arctic Nations

A = Agricultural drying, B = Bathing and swimming (including balneology), D = District heating, F= Fish farming, G = Greenhouses and soil heating, H= Individual space heating, I = industrial process heat, K = Animal farming, and S = Snow melting.

Sources: Lund et al. (2020), Ragnarsson (2015)

Country	Number of Systems	MWth	TJ/yr	Application
United States	469	482.63	7,349.3	BDFGHIKS
Russia	No data	421	8,380	ABDFGHIK
Iceland	No data	2,367	33,579	BDFGIS
Greenland	1	0.1	3.2	B
Canada	13	8.78	277	B
Norway	1	0.18	1.20	S
Sweden	0	0	0	none
Finland	0	0	0	none
TOTALS	**484**	**3,280**	**49,590**	

4.4. Geothermal Electricity (>80°C)

In geothermal electrical production, hot fluids extracted from a subsurface reservoir provide power to a community (DOE 2021). Geothermal energy serves as the baseload while backup energy sources such as diesel are brought in through the supply chain, and other sources such as wind or hydroelectric may likewise be incorporated into the grid (Cook, Davíðsdóttir, and Kristófersson 2016; Devine et al. 2004; Hardarson et al. 2018; Isherwood et al. 2000; Lovekin, Dronkers, and Thibault 2016). After producing power, the spent fluids are reinjected back into the reservoir to maintain the productivity of the geothermal system.

Three out of the eight Arctic countries have geothermal power plants: the United States, Iceland, and Russia. However, only Iceland hosts a significant number of geothermal power plants in a subarctic climate. Only one US geothermal plant is located in the subarctic (Alaska), and none are located in the Arctic. The United States has the greatest installed geothermal capacity worldwide at 3700 MW from 99 power plants, concentrated in the western part of the country (Huttrer 2020; Robins, Kolker, and Espino in preparation). Iceland has eight geothermal power plants, which provide 62% of the country's energy production (Huttrer 2020). Russia has five geothermal power plants total, three of which have an installed capacity greater than 5 MW. Those plants are all located on Russia's Kamchatka peninsula (Svalova and Povarov 2020;).

4.5. Geothermal Cascaded Use and Integrated Heat and Power Systems

Cascaded use is also known as polygeneration, which is an integrated system that produces multiple products from one resource, increasing efficiency and economic benefits (Rubio-Maya et al. 2015). Cascaded use of geothermal heat either can apply to purely direct-use applications, or for both power and heat. Like CHP, cascaded use involves the repurposing of waste heat rejected from one process to another process. Geothermal fluids can be "cascaded" from one application, such as the production of electricity, to lower-temperature applications such as ice production using absorption chilling, to even lower-temperature applications such as building or greenhouse heating, prior to being reinjected into the reservoir (Ambriz Díaz et al. 2015). Geothermal cascaded use can supply all the energy needs of a community (Rubio-Maya et al. 2015).

GDH systems can be associated with cascaded use of geothermal energy. In Iceland, Reykjavik's waterworks and sewer system are part of the city's district heating system, whereas the district heating system used for the city of Klamath Falls and the Oregon Institute of Technology is responsible for snow melting (Lund and Toth 2021; Ragnarsson et al. 2020). Four of Iceland's eight geothermal power plants use their waste heat for various direct-use applications. The Svartsengi power plant provides hot water to the town of Reykjanes, heating and seawater drying for the famous touristic attraction the Blue Lagoon, and it makes methanol from CO_2 emissions of the plant. Hellisheidi and Nesjavellir are both co-generation power plants that provide district heating for the town of Reykjavik, while Fludir is another CHP plant providing district heating and heat for greenhouses (Ragnarsson, Steingrímsson, and Thorhallsson 2020; Rubio-Maya et al. 2015).

Large-scale, grid-connected geothermal CHP systems, wherein communities use both heat and power to meet several energy demands, are relatively rare in the Arctic because large-scale demand centers (cities) must be co-located with a high-temperature resource. Examples of such systems in Arctic countries include four systems in Iceland, two systems in the United States, and possibly in Kamchatka, Russia (unverified). In these systems, hot fluids from a geothermal reservoir are extracted from a wellfield, where production wells supply steam or hot water to the geothermal power plant. Spent fluids from the power plant are almost always still warm enough to supply heat to the community for a variety of applications before being reinjected back into the reservoir. However, depending on the distance between the power plant and offtakers of the heat, they are not always fully exploited due to the costs and logistics of piping and distribution.

Iceland and the United States are the only Arctic countries with documented cascaded use projects, and a significantly larger portion of Iceland's geothermal energy production involves cascaded use. In Iceland, 66% of power plants cascade spent fluids for direct-use applications, whereas only 0.2% of power projects in the Unites States do so. Of the geothermal direct-use applications in Iceland, 28% use hot fluids cascaded from geothermal power plants, whereas only 1.3% geothermal U.S. direct-use applications use fluids cascaded from power plants (Rubio-Maya et al. 2015; calculated from data sourced from Huttrer 2020; Ragnarsson, Steingrímsson, and Thorhallsson 2020). The Oregon Institute of Technology in the United States has a co-generation plant that saves $1 million a year in heating costs by using geothermal fluids to heat the campus as well as community buildings in the town of Klamath Falls, with waste heat cascaded for agriculture, including both greenhouse heating and aquaculture (Brophy, Lund, and Boyd 2015; Rubio-Maya et al. 2015; Sifford 2014).

Geothermal power plants sometimes use other power sources as emergency backup or to contribute to power production. The Pauzhetka plant (Russia) operates in conjunction with four diesel generators which add to the already existing power production (Svalova and Povarov 2020). In Iceland, hydropower plants mitigate problems with fluctuations in the grid, while diesel generators that used to function as emergency backup at the Hellisheidi and Theistareykir geothermal power plants are no longer permitted (Hallgrímsdóttir, Ballzus, and Hrólfsson 2012; Hardarson et al. 2018); Thorsteinsson 2021). At Theistareykir, the plant's location in the weak northeastern section of the Icelandic electrical grid makes it especially prone to blackouts and being overloaded (Hardarson et al. 2018).

Remote geothermal systems exist in both the United States and Russia, and smaller microgrids exist in Iceland. The 0.68-MW plant at Chena Hot Springs, Alaska, combines heat and power by cascading geothermal brine after it used for electrical production for heating and cooling applications (Brophy, Lund, and Boyd 2015). First, thermal waters are used to cool the year-round ice museum through an absorption chiller, and then subsequently provide heat for district heating, greenhouses and pools (Robins, Kolker, and Espino, in preparation). The system offsets 135,000 gallons of diesel a year for heat and 105,000 gallons of year for power, although does rely on a diesel generator in addition to the geothermal power plant (Brophy, Lund, and Boyd 2015). In Russia, two 3.6-MW power plants on the Kuril Islands, Okeanskaya and Mendeleevskaya, are used only for electrical generation (Svalova and Povarov 2020). A schematic of a hypothetical remote geothermal system serving an off-grid community is given in Figure 6.

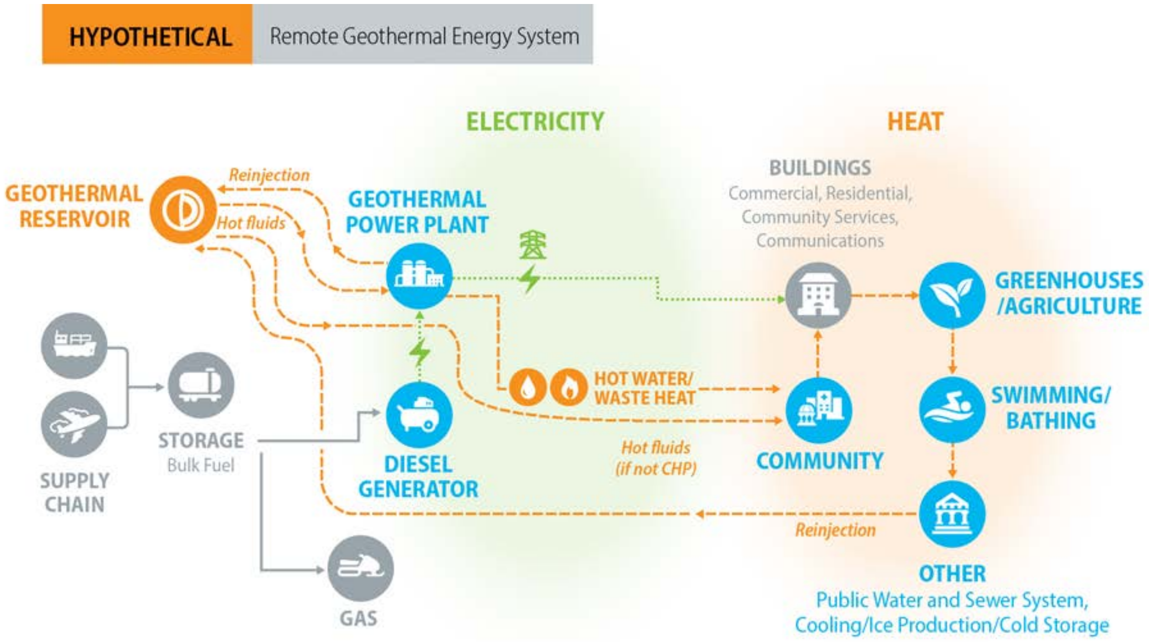


Figure 6. Schematic remote geothermal energy system providing heat, power, and other services to a hypothetical off-grid community in an Arctic country

5. Innovative Technologies and Uses of Geothermal Energy for Arctic Countries

5.1. Microgrid-Scale Power Generation Technologies

Geothermal technology can provide power and/or heat at the microgrid scale. Many small projects, both grid-connected and isolated, have successfully operated for years. Also, small geothermal technology and systems continue to improve.

Similar to a steam Rankine cycle, but with an organic working fluid with a lower boiling temperature than water, organic Rankine cycle (ORC) plants are a good choice for small geothermal systems with lower-temperature sources. Compared to steam plants, ORC plants have higher pump losses, lower efficiency (up to 24%) and require more working fluid, but the lack of condensation increases turbine blade life, lower pressure eases heat recovery, lower temperature reduces stresses on components, lower enthalpy drop allows simpler turbine designs, lower rotating speeds lead to less blade stress and enables the use of robust direct drive generators, and no on-site operator is needed (Quoilin et al. 2013). Recent bottoming cycle technology and recuperators can further increase efficiency (Batir and Richards 2019). Overall, the lower capital and operating costs of ORC systems make them preferable to steam plants for lower-temperature sources. For higher-temperature sources, CHP systems using ORC plants can increase overall energy efficiency by utilizing the organic fluid to heat water after passing through the turbine.

Modular ORC systems were a well-proven technology for mid- to high-temperature resources by the 1980s, with high reliability and low maintenance costs. ORC design continues to improve, particularly with respect to modularization and optimization for lower temperatures (70°–120°C). Some companies are mass producing ORC units, which lowers costs through economies of scale; increases reliability, resale value, and part availability; and enables lower financing rates (Havsed and Skog 2018). New conversion technologies such as vacuum supercritical cycle are also helping drive down costs. The smaller the system, the more drastic the decrease in capital costs with manufacturing volume. Compared to using custom designs, using mass-produced standardized designs yields potential increases in net present value of $1.4 million for a given 5-MWe ORC system (Akar et al. 2018). Optimization of whole-system design has also improved the economics for smaller systems (e.g., sizing a low-enthalpy geothermal plant with thermal degradation considerations [Gabbrielli 2012]). The small footprint of ORC technology minimizes land use and is flexible, redundant, and resourceful (since maintenance can occur one-module-at-a-time while the rest continue operating). Modular development also enables earlier power generation during development (Havsed and Skog 2018).

5.2. Advances in Small-Scale Power Generation Technologies

Beyond continued improvements in the performance and costs of ORC units, other technological innovations for small geothermal power systems include the mass production of ORC units, the use of slimholes and wellhead generation, and optimized design points.

5.2.1. Mass-Produced ORC Systems

A techno-economic consideration for small geothermal ORC systems is whether to use mass-produced, standardized designs or custom designs. An NREL study (Akar et al. 2018) demonstrated the trade-off between custom designs, which are more expensive but tailored to a site-specific design point, or standardized designs, which are less expensive and suited to a range of off-design resources. Their detailed analysis of a 5-MWe system revealed a potential increase in net present value of $1.4 million for standardized designs. For a 1-MWe system, capital costs decreased drastically with manufacturing volume, through the leveraging of economies of scale (Akar et al. 2018). However, this design choice may depend on the resource mass flowrate and temperature. At higher flowrates and temperatures, standard designs are favored.

5.2.2. Producing From Slimholes

Traditionally, large-diameter (>6”) wells are used for geothermal power plants. This makes sense for large geothermal power plants, which require a high brine flowrate. However, smaller plants could benefit in cost and environmental impact by using slimholes. Slimhole drilling is typically one-third the cost of rotary drilling, which is used for larger holes. One study predicted that a 300-kW plant with a 120ºC resource could produce power at 11¢/kWh, which would be competitive in most remote markets, even without drilling cost savings (Combs, Garg, and Pritchett 1997). Garg developed optimized slimhole casing designs, which could increase discharge capacity by 200%, further increasing rated power (Garg et al. 2000). Depending on the brine temperature, slimholes can supply more than 1 MWe. This energy capacity is undisputed, along with the preferred designs: for resources above 150ºC, self-discharge is preferable, otherwise a submersible pump is necessary. Plants are available and practical: below 170ºC, a binary or low-temperature single-flash condensing steam turbine is preferable; above 170ºC, a high-pressure condensing steam turbine is preferable (Finger 1999). There are environmental benefits as well, such as lower land use, air pollution, and noise pollution, along with less drilling fluid to dispose of (Do et al. 2019). The main challenge with this concept is that it is untested: a pilot slimhole plant is required for validation. Finally, fracture detection and borehole/casing inspection tools need to be developed for slimholes. Proposed slimhole projects include a geothermal hot water project in Indonesia (Aalten et al. 2018) with an estimated 7- to 8-year payback period, and a geothermal electricity project in Vietnam (Geirdal 2015).

5.2.3. Wellhead Generation

Traditionally, in a geothermal project with multiple wellheads, drilling and power plant installation are performed in series. Newer projects with smaller power plants use the “wellhead method,” wherein modular ORC units are installed on each well in parallel with continued drilling. This approach has several advantages, including reduced time until energy production begins, more efficient exploitation of wells at varying temperatures and pressures, resilience due to modularity, transportability, the elimination of large steam-gathering systems, and utilization of remote wells. Disadvantages include longer transmission lines, higher cost/kW per unit, more electrical equipment, a separation station for each plant, and reinjection during drilling. Overall, wellhead plants could increase system power and net present value by up to 5% and 16%, respectively (Geirdal 2015). In addition, reduced flowrate requirements for newer-generation units could take advantage of slimholes rather than traditional large-diameter geothermal wells. Slimholes can theoretically supply more than 1 MWe with optimized slimhole casing designs to increase discharge (Garg et al. 2000). This could mean that a 300-kW plant with a 120°C resource could produce power at 11¢/kWh, which is competitive in many remote markets (Combs et al. 1997). The slimhole concept is untested, but proposed projects include one in Indonesia (Aalten et al. 2018) with an estimated 7–8 year payback period, and one in Vietnam (Do et al. 2019).

5.2.4. Optimized Well Design Points

Using a detailed performance model, Gabbrielli showed that under a variety of scenarios, designing a small, low-enthalpy geothermal plant using the lowest temperature of the geothermal resource during its operative life is always economically optimal. This optimized design point prevents the need to resize a small geothermal plant after thermal degradation (Gabbrielli 2012).

5.3. Examples of Geothermal Microgrids

Following are examples of successful and unsuccessful small geothermal microgrids, both isolated and grid-connected.

Fang Geothermal System: Grid-Connected

The Fang geothermal microgrid near Chang Mai, Thailand, utilizes a low-temperature source (116ºC) with an ORC system in continuous operation since 1989. The plant produces 150–250 kWe, with seasonal variation, and waste heat is used for cold storage, crop drying, and a spa. This synergy improves project economics. Excellent project maintenance has yielded an availability of 94%, with an estimated LCOE of 6.3–8.6¢/kWh. This demonstrates a small power plant with old technology and a low-temperature resource producing reliable, inexpensive power and providing heat to other local industries (Kaplan and Shilon 1999).

Nagqu Geothermal System: Isolated

The Nagqu geothermal power plant was an isolated ORC geothermal system in Tibet, utilizing a low-temperature source (110ºC) with an ORC system, commissioned in 1993. Although this system provided far cheaper power than the diesel generators it replaced, it was plagued with technical problems (Yamada and Oyama, n.d.). The plant employed two wells with downhole pumps to keep the heat exchangers above fluid saturation pressure to prevent scaling. However, these pumps consumed 60% of the gross power output. Fifteen days after commissioning, a pump seal failure shut down well #2. Eighteen days after that, a failure in the plant control computer shut the whole plant down. The computer took five months to repair, after which well #1 resumed operation. Seven months later, its pump failed due to an electrical fault, and the whole plant become idle for 3.5 years. Anti-scalant injection was implemented to replace the failed downhole pumps. As much local support and sourcing as possible was used, as the complex equipment initially used proved difficult to maintain by the local workforce. The plant was recommissioned in 1998, but after a couple months it failed due to a governor amplifier failure, which the local staff were unable to troubleshoot. The plant was restarted in April 1999 with the help of technicians from Jingmen, but it shut down four days later due to a mechanical seal failure on the binary fluid cycle pump and has not operated since.

On the surface, the Nagqu plant failed due to technical equipment failure. However, shoddy equipment is likely not the root issue, which is probably the combination of several factors: Nagqu’s remote location increasing travel time and cost, harsh climatic conditions affecting the well-being and attitude of the workforce, inexperienced staff, lack of spare parts access extending delays, language difficulties hampering training, limited organization and infrastructure making plant management and operation difficult as well as affecting foreign procurement, issues integrating with the local distribution system, lack of local sourcing, and the use of complex technology beyond the level of local knowledge. This project highlights the need for innovative, inexpensive solutions to deal with problematic geothermal fluids, as well as the need to develop systems that can be understood, operated, maintained, repaired, and managed proficiently by the local workforce (Low and Morris 2000). A project must not only be technically and economically feasible, but also socially and practically feasible.

5.4. Other Economic Development Opportunities From Remote Geothermal Resources

In Iceland, hydrogen has been produced from water with electrolysis since 2003, using electricity from geothermal plants. At the Hellisheiði Geothermal Power Plant, non-condensable gases have been injected into the ground since 2014 (RÚV 2014), and an electrolyzer is planned to be installed for hydrogen production (Iceland Monitor 2018). The potential to create two economically valuable products from gas emissions improves the economics of geothermal development, and offers economic development opportunities in areas where such opportunities are sparse.

Geothermal steam may contain hydrogen sulfide (H_2S) (Nagl 1999), which can pose environmental and health concerns during geothermal development (Meder 2013; Karapekmez and Dincer 2018), but can be converted into hydrogen (H_2) and sulfur (S), both of which are economically valuable. Elemental sulfur is used in detergents, batteries, fertilizers, fungicides, corrosion-resistant concrete, and sulfuric acid (Nagl 1999; Ghahraloud, Farsi, and Rahimpour 2018). Hydrogen is considered a valuable energy resource and is used in various large-scale chemical processes, including ammonia and methanol synthesis, oil processing, and petrochemistry (Startsev 2017; Ouali et al. 2011). Various methods have been developed to produce hydrogen from hydrogen sulfide, but they typically fall into two main categories: chemical methods and thermal methods. Chemical methods include photochemical (Dan et al. 2020), electrochemical (Karapekmez and Dincer 2018), and plastochemical (Startsev 2017) processes, while thermal methods include thermal decomposition and closed thermochemical cycles (Startsev 2017). Geothermal plants can provide a direct source of hydrogen and elemental sulfur, as well as the heat and electricity required for electrochemical and thermochemical methods of hydrogen production (Arnason and Sigfusson 2007).

6. Resilience Attributes of Geothermal Integrated Energy Systems in Arctic Countries

6.1. Large-Scale, Grid-Connected Power

As established in Section 3, electrical resilience can be broken up into four attributes: reliability, redundancy, resourcefulness, and response. Each answers a different question:

- Reliability: How does the system perform in typical conditions?
- Redundancy: Are there single points of failure?
- Resourcefulness: How are the needed resources utilized?
- Response (Recovery): Can the system bounce back from disruption?
- Response (Operations): Is the power system stable and able to provide ancillary services?)

The tables in the following subsections show how geothermal performs under a variety of resilience questions, applicable to both microgrid and grid-connected contexts. The tables are color coded: green means geothermal excels, yellow means geothermal is average, and orange means geothermal performs poorly relative to other generation sources.

6.1.1. Theoretical Case for Grid-Connected Geothermal Power

Grid-connected geothermal power is a widely proven technology whose reliability will be enhanced by the adoption of mass-produced modules, with higher quality control. Although geothermal can be unstable in low-load operation, this can be mitigated with storage, capacitors, and other technology. In a grid-connected scenario, there is more flexibility in dispatch, so geothermal can be kept at high output, capitalizing on its free fuel source and avoiding low-load.

Utilizing multiple modular units provides redundancy in the grid context, and fuel storage is unnecessary, reducing system complexity. The long timescale variability of the geothermal resource enhances its resourcefulness. Geothermal can recover from external events: it is little affected by natural disasters (apart from earthquakes and volcanic eruptions), and modular systems can respond to resource variation by operating at different set points. In case of an internal system failure, spare parts are readily available for mass-produced modules. Finally, geothermal systems can support black start to restart the grid in the case of a blackout.

Geothermal systems can provide ancillary services to stabilize the grid. Puna Geothermal Venture (PGV) and the Geysers geothermal power plants operate as baseload, and provide load following, spinning reserve, and peaking power. The Puna plant engages in frequency and voltage response (Matek 2015). When providing spinning reserve, excess geothermal heat could be reinjected into the well, or used for heating and heat storage. Also, when grid-connected, the geothermal plant will provide system inertia from its generator.

ORC plants like PGV are well-suited to provide ancillary services. Curtailment is accomplished with bypass valves, and flexible operation does not change operation and maintenance (O&M) costs. Ramp is typically 15% nominal power/minute, up to 30% (Matek 2015). Flash plants like the Geysers can also provide ancillary services but are less ideal. Bypass valves are quick to implement but increase O&M costs and resource depletion. Alternatively, gradually throttling back production wells can increase thermal cycling and is slower but conserves the resource. Dry steam plants can also provide ancillary services but have increased O&M and equipment costs (Matek 2015).

Using geothermal to provide ancillary services is not widely implemented and requires further validation at new projects. This is likely due to the lack of incentive to provide grid ancillary services in the past (Matek 2015). The main uncertainty is the effect of geothermal resource variation on its ability to provide ancillary services. However, the long timescale of the variability suggests that it will have little effect on such short timescale operation. Edmunds et al. (2014) proposed using reservoir management to compensate for imbalances between grid load and generation. Geothermal could do this in two ways. First, geothermal energy withdrawal from the reservoir could be scheduled to match the grid's needs. Second, parasitic load could be time-shifted to adjust the net power output by cycling injection and reservoir pressure. This would only apply to over-pressurized reservoirs. Either way, variable heat withdrawal could be conducted on a diurnal basis to allow for increased power output during high electricity demand periods.

The performance of a theoretical geothermal power plant in terms of resilience attributes is summarized in Table 6.

Table 6. Performance of a Theoretical Geothermal Power Generation Plant (Utility-Scale) Considering Resilience Attributes and Relevant Components of the System

Green: geothermal excels; Yellow: Geothermal is average; Orange: geothermal performs poorly

Resilience Attribute	Component	Performance of Geothermal Power Grids
Reliability: How does it perform in typical conditions?	Wellfield	🟨 Depends on resource type and reservoir management
	Generation equipment	🟨 Depends on the supplier. Mass-produced modules increase system quality control
	Balance of system equipment	🟨 Similar to other sources
	Low-load operation	🟧 Hard to ramp down/unstable under low load. Can mitigate with storage, capacitors, other technology
Redundancy: Are there single points of failure?	Fuel storage	🟩 Not implemented
	Number of generators	🟨 Small modules allow redundancy in larger systems, although microgrid may only have one module
	Need for backups	🟨 Not if have multiple modules or on large grid
Resourcefulness: How are the needed resources utilized?	Critical transportation routes (fuel/supplies)	🟩 No fuel supply chain after construction. Small systems with slimholes require smaller equipment
	Workforce	🟧 Need for local education/training
	Variation in resource	🟩 Low variability. Large timescales (years). Can design plant to operate at end-of-life well conditions to maximize total output and minimize variability
	Infrastructure needs	🟨 Modular systems require less
Response (Recovery: can the system bounce back from disruption?)	Natural disasters (weather-related)	🟩 Not susceptible to weather-related disasters
	Natural disasters (geologic hazards)	🟨 Depending on location, can be susceptible to earthquakes and volcanic eruptions
	Response to variation in resource	🟨 Modular systems can operate at different set points
	Spare parts	🟩 Readily available for mass-produced modules
	Black start	🟩 Geothermal is capable of black-start support.
Response (Operations: is the power system stable and able to provide ancillary services?)	Switching capability	🟨 Possible but not widely implemented
	Ramp up/down	🟨 Possible but not widely implemented
	Reserve capacity/spinning reserve	🟨 Possible but not widely implemented. Could use storage/demand-side management for this. Could use excess power for heating and heat storage
	Inertial response	🟩 Yes, if synchronous
	Frequency response	🟨 Possible but not widely implemented
	Voltage response	🟨 Possible but not widely implemented

6.1.2. Case Study 1 for Grid-Connected Geothermal Power: Puna

Puna Geothermal Venture (PGV) is the first geothermal plant designed to be dispatchable, providing a variety of ancillary services, and has been commercially operated since 2012 on the big island of Hawai'i. Flexible operation has not increased the plant's O&M costs. The plant consists of ten 3-MW modular geothermal combined cycle units (GCCUs) in addition to two binary cycle bottoming ORC units that increase the capacity by 8 MW. The plant is dispatchable between 22 and 38 MW, it can perform a 2-MW/min ramp with an additional quick load pick up of 3 MW spinning reserve in 3 seconds, it has a 4% frequency droop for frequency regulation, and it is capable of regulating voltage via reactive power control as well. As such, the plant can provide spinning reserve, frequency response, and voltage response. When the power command decreases, the bottoming cycle units are dispatched down first, followed by the GCCUs, followed by the opening of steam turbine bypasses in emergencies. Excess organic vapor is maintained to provide spinning reserve and dumped into the condenser when not needed. The grid commands the system with active generation control, which communicates with the plant's Supervisory Control and Data Acquisition (SCADA) system. The active generation control communicates required net power, grid frequency, and grid voltage to the SCADA system, and the SCADA system responds with current spinning reserve, current upper limit for available dispatch, and current lower limit for available dispatch (the minimum stable generation). This communication allows PGV to automatically adjust its power output according to grid needs. The PGV system is redundant in that only 9/10 GCCUs are needed for full capacity, so one at a time can be offline for maintenance without reducing output. Designing such a novel system had a variety of technical challenges, especially retrofitting the old GCCUs, which had operated for a decade prior (Nordquist, Buchanan, and Kaleikini 2013).

PGV enhances the resilience of the Hawaiian grid in a variety of ways. The redundant system allows the plant to maintain full operation during maintenance or a module fault. It is not dependent on expensive fuel imports to the island, and is relatively immune to extreme Pacific weather. It provides ancillary services to the grid, following load, supporting grid frequency and voltage, and providing inertia. It has the technical potential to support black start, although it is unknown if it is ever used to do so. To support black start, it needs to be large enough relative to the grid, and in the right position in the grid.

The performance of a the PGV geothermal power plant in terms of resilience attributes is summarized in Table 7.

Table 7. Resilience of Key System Components of the Puna Geothermal Venture Power Plant in Hawaii, USA (PGV)

Green: PGV excels, Yellow: PGV is average, Orange: PGV performs poorly

Resilience Attribute	Component	PGV Performance
Reliability: How does it perform in typical conditions?	Wellfield	🟩 No known issues
	Generation equipment	🟩 Mature technology (Ormat ORC)
	Balance of system equipment	🟨 Not evaluated
	Low-load operation	🟨 Flexible within typical grid requirements. Low-load operation unknown (beyond turndown from 38 to 22 MWe) but likely possible.
Redundancy: Are there single points of failure?	Fuel storage	🟩 Not implemented
	Number of generators	🟩 12
Resourcefulness: How are the needed resources utilized?	Critical transportation routes for fuel and supplies	🟩 No fuel supply chain after construction
	Power sector workforce	🟨 Not evaluated
	Variation in resource	🟩 Low variability. Large timescales (years). Can design plant to operate at end-of-life well conditions to maximize total output and minimize variability
	Infrastructure needs	🟨 Not evaluated
Response (Recovery: Can the system bounce back from disruption?)	Natural disasters (weather-related)	🟩 No outages due to weather-related disasters reported
	Natural disasters (geologic hazards)	🟧 Offline 2018–2020 due to volcanic eruption
	Response to variation in resource	🟩 Modular systems can operate at different set points
	Spare parts	🟨 Available but long supply chain vulnerable to disruptions
	Black start	🟨 Has technical capability. Unknown if this is exploited.
Response (Operations: Is the power system stable and able to provide ancillary services?)	Switching capability	🟩 Yes
	Ramp up/down	🟩 Yes
	Reserve capacity/spinning reserve	🟩 Yes
	Inertial response	🟩 Yes
	Frequency response	🟩 Yes
	Voltage response	🟩 Yes

6.2. Geothermal Microgrids

Geothermal energy is technically capable of operating in a microgrid setting (Kaplan et al. 1999). Recent experiences, combined with advances in power generation and control technology, show that geothermal microgrids can meet local demand and also provide the range of grid services and ancillary services required for a system to operate in a safe, reliable, and stable manner. Though geothermal power plants do not typically provide all of the grid services that would be required by remote microgrids, that has historically been for economic reasons rather than technical limitations (Edmunds et al. 2014; Matek 2015). As a synchronous generating source (i.e., involving a physical element spinning at the same alternating current frequency as the power system), geothermal has an advantage over current inverter-based renewable microgrid technologies because it can naturally provide inertial and frequency response (Ahmed et al. 2015). The PGV is an example of a geothermal system providing such services. Geothermal also offers black-start capability, which is necessary to restart a microgrid in case of a blackout, and is not provided by inverter-based resources if they are configured to be grid-following.

The ability of geothermal to provide ancillary services in a microgrid context is more crucial than in a grid-connected context. Microgrids experience more significant swings in load, so geothermal must maintain a stable grid by ramping quickly, and providing spinning reserve, frequency response, voltage response, and inertia to the system. These functionalities have been demonstrated in the PGV grid-connected system, but not in microgrid systems. While geothermal can operate flexibly with an adjustable power output, typical ramp rates are slower than comparable diesel or gas turbines, and cyclical up/down operation can lead to more rapid degradation of geothermal equipment and increased O&M costs (Edmunds et al. 2014). Hence, although a geothermal system can technically serve a microgrid as the sole source of power, it may still be beneficial—though not technically necessary—to deploy geothermal in configurations together with diesel generators, batteries, or other energy storage to support rapid switching and ramping response, and also serve as a backup. Geothermal microgrids have low susceptibility to extreme weather, though they could be susceptible to geologic hazards such as earthquakes and volcanic eruptions. Geothermal microgrids have higher resourcefulness than diesel-based microgrids due to the latter's expensive and often unreliable transportation routes for fuel and supplies. Local education and training in geothermal technology is necessary, but also provides local job opportunities to avoid expensive service trips from outside engineers and technicians. Finally, the effects of geothermal on existing generation must be considered. For instance, when adding geothermal to existing diesel systems, diesel generator performance may degrade from increased switching and decreased load factor (Vander Meer and Mueller-Stoffels, n.d.)

6.2.1. Geothermal Microgrid Theoretical Case Study

As each generator in a microgrid comprises a larger fraction (or even all) of the microgrid generation, their role in providing resilience becomes more critical. Some attributes particularly important for microgrids are highlighted next.

Redundancy and recovery are of key importance when the geothermal plant comprises a large fraction or all of generation. In a microgrid, if only one module is used, the system is not redundant, and a backup generator is necessary. The low susceptibility of geothermal installations to extreme weather and natural disasters (apart from earthquakes and volcanic eruptions) enhances its recovery potential. Finally, geothermal must engage in black start to restore grid power in case of a blackout.

Geothermal resourcefulness excels in remote microgrids, which likely have expensive and unreliable transportation routes for fuel and supplies. For instance, most remote Arctic communities require diesel fuel to be barged for generators, which is very expensive and weather dependent. The use of slimholes requiring relatively small equipment allows smaller transportation routes to be used for geothermal during construction and maintenance runs, and the geothermal fuel is local, so no fuel supply chain is needed after construction. However, additional local education and capacity building in geothermal technology is necessary to equip the workforce, as trips from outside engineers and technicians are more expensive.

6.2.2. Case Study for Geothermal Microgrid: Chena, Alaska

A 680-kWe isolated geothermal microgrid has been operating in Chena Hot Springs, Alaska (Chena) since 2006 (Alaska Energy Wiki 2012). Chena is a remote off-grid community near Fairbanks, Alaska, that uses geothermal energy for several cascading uses, including power and direct use. The power plant utilizes the lowest-temperature geothermal electricity source in the world, 71ºC, with power generation made efficient by the availability of near-freezing river water and seasonal subzero air temperatures. The geothermal plant offsets diesel generation, and for the first two years of the project, electric costs were reduced from 30¢/kWh to 5¢/kWh ("Chena Geothermal Area | Open Energy Information" n.d.), resulting in savings of more than $650,000 in diesel fuel in the first year of operation (Holdmann 2007). Waste heat is used for district heating, greenhouses, a spa, and other uses including seasonal cooling. Seasonal cooling is needed for the Aurora Ice Museum at Chena, a combination museum/hotel serving the resort's visitors. The Ice Museum is entirely built from ice and requires cooling during summer months. To provide cooling, an absorption chiller was installed in 2005 that runs on 73°C geothermal heat and provides 15 tons of -29°C chilling, allowing the Ice Museum to stay frozen year-round. The chill brine (a $CaCl_2$ solution) circulates through an air handler, which cools an annular space in the ice hotel between the ice walls and the external insulation (Erickson and Holdmann 2005).

The geothermal system makes Chena less dependent on uncertain, weather-dependent, expensive fuel supply routes. The addition of multiple geothermal units further increased the redundance of the system. If any generator goes offline, there is more than enough generation to maintain the system. However, over time, the original, custom-built ORC units had maintenance issues, which required company representatives to service. This cost and unreliability led to their replacement with mass produced generators that remain to this day. This highlights the need for better-understood, mass-produced systems that can be maintained with local resources over custom builds. Overall, the plant has operated successfully, with some modifications over the years related to the geothermal supply, the cold-water supply, and the injection scheme.

The performance of the Chena geothermal power plant in terms of resilience attributes is summarized in Table 8.

Table 8. Resilience of Key System Components of the Geothermal Microgrid at Chena Hot Springs, Alaska (CHS)

Green: CHS excels, Yellow: CHS is average, Orange: CHS performs poorly

Resilience Attribute	Component	Performance of the CHS Microgrid
Reliability: How does it perform in typical conditions?	Wellfield	🟩 Initial reservoir management issues now resolved
	Generation equipment	🟩 Diesel generators + 3 binary geothermal modules (custom built modules replaced with mass-produced modules)
	Balance of system equipment	🟨 Not evaluated
	Low-load operation	🟨 Custom units were difficult to ramp down/up, but new mass-produced units perform well under low loads
Redundancy: Are there single points of failure?	Fuel storage	🟨 Not evaluated
	Number of generators	🟩 3 small modules allow redundancy
Resourcefulness: How are the needed resources utilized?	Critical transportation routes for fuel and supplies	🟩 No fuel supply chain after construction
	Power sector workforce	🟨 Initial need for specialized technicians but O&M managed by local staff
	Variation in resource	🟩 Low variability. Large timescales. Can design plant to operate at end-of-life well conditions to maximize total output & minimize variability
	Infrastructure needs	🟨 No significant transmission needs
Response (Recovery: Can the system bounce back from disruption?)	Natural disasters (weather-related)	🟩 No outages due to weather-related disasters reported
	Natural disasters (geologic hazards)	🟩 No negative effects from historical earthquakes
	Response to variation in resource	🟨 Modular systems can operate at different set points
	Spare parts	🟩 Readily available for mass produced modules
	Black start	🟩 Black start provided by diesels and batteries
Response (Operations: Is the power system stable and able to provide ancillary services?)	Switching capability	🟩 Can switch and synchronize within seconds
	Ramp up/down	🟨 Ramp geothermal with throttle valves
	Reserve capacity/spinning reserve	🟩 Diesels serve as spinning reserve
	Inertial response	🟩 Yes (synchronous)
	Frequency response	🟨 Not evaluated
	Voltage response	🟨 Not evaluated

6.3. Integrating Thermal Energy

6.3.1. Geothermal District Heating (GDH) Theoretical Case

Direct use of geothermal energy for district or space heating makes a lot of sense. Space heating is typically the largest energy need in Arctic countries, and it can be met with a relatively low temperature geothermal source. Table 9 provides an examination of the resilience attributes of GDH. The gray sections are independent of the energy source in application. However, addressing some of the gray sections can improve the ability of geothermal direct use to meet capacity. For example, building-level heat distribution and envelope insulation will dictate the required temperature of the resource. Well-insulated buildings with in-floor heat delivery can function with district heat temperatures as low as 30°C, but radiator delivery systems need at least 70°C fluid. The performance of a theoretical geothermal GDH system in terms of resilience attributes is summarized in Table 9.

Table 9. Resilience of Key Components of a Theoretical GDH System

Green: geothermal excels, Yellow: Geothermal is average, Orange: geothermal performs poorly,
Gray: performance is independent of the energy source

Resilience Attribute	Component	Performance of GDH system
Reliability: ***Does it perform in typical conditions?***	Maintenance plans	Independent of source
	Performance monitoring	Independent of source
	Age of system/components	Independent of source
	Maintain outage stats	Independent of source
Redundancy: ***Are there single points of failure?***	Multiple heat plants	Multiple wells can be expensive
	Multiple heat sources	Geothermal is the only source
	Redundant workforce	Currently the workforce does not exist
	Redundant pumps	Independent of source
Resourcefulness: ***Are there diverse and flexible options?***	Building level thermal resilience	Independent of source
	Meshed distribution systems	Independent of source
	Ability to exceed design capacity in extreme cold events	Can be developed
	Thermal storage capacity	Can be developed
	Ability to meet multiple temperature delivery needs	Can be developed
	Time to recovery—thermal resilience of buildings in the system	Independent of source
	Ease of recovery—supply chain flexibility	Excellent
Recovery: ***Can system bounce back from disruption?***	Standardized parts and supplies	Excellent
	Plan for recovery	Independent of source
	Spare parts inventory	Independent of source
	Workforce for recovery	Independent of source

6.3.2. *Case Study for Geothermal District Heating: Reykjavik, Iceland*

The NREL team interviewed staff at Reykjavik Energy to learn about how the multiple GDH systems in Reykjavik perform using the established resilience metrics. Results of that interview, supplemented with additional information from the literature, is provided in Table 10.

Table 10. Resilience of Key Components of Reykjavik's GDH System (RGDH)

Green: RGDH excels, Yellow: RGDH is average, Orange: RGDH performs poorly. Gray: performance is independent of the energy source

Source: H. Thorssteinsson, Reykjavik Energy, *pers. communication* (2021)

Resilience Attribute	Component	Performance of Reykjavik GDH
Reliability: ***Does it perform in typical conditions?***	Maintenance plans	Very developed
	Performance monitoring	Yes
	Age of system/components	Regular replacement schedule
	Maintain outage stats	Yes, outages are extremely rare
	Leakage detection system	Regular piping checks with in-pipe robots
Redundancy: ***Are there single points of failure?***	Multiple heat plants	Two high-temp. CHP plants, 4 low temp. plants
	Multiple heat sources	Multiple wells from multiple geothermal fields
	Redundant workforce	Long-serving system (since 1930), large workforce
	Redundant pumps	Redundancy in the main parts of the system, less redundant toward the end of the lines
Resourcefulness: ***Are there diverse and flexible options?***	Building level thermal resilience	Not evaluated
	Meshed distribution systems	The main parts of the system have piping from multiple directions
	Ability to exceed design capacity in extreme cold events	Can redirect CHP steam and change mixing temperatures
	Thermal storage capacity	Able to meet requirements without thermal storage
	Ability to meet multiple temperature delivery needs	Yes, uses temperature mixing valves
	Time to recovery—thermal resilience of buildings	Not evaluated
	Ease of recovery—supply chain flexibility	Not necessary due to lack of supply chain
Recovery: ***Can system bounce back from disruption?***	Standardized parts and supplies	Yes
	Plan for recovery	None
	Spare parts inventory	Yes
	Workforce for recovery	Yes

6.3.3. *Resilience of Geothermal Cascaded Use*

Space heating is typically the largest energy need in Arctic countries, and can be met with a relatively low-temperature geothermal source. Cascaded use is resourceful—it produces multiple products from one resource, increasing efficiency and economic benefits (Rubio-Maya et al. 2015). While low-temperature resources used only for power production have low net efficiency due to low Carnot (theoretical) efficiency and high parasitic loads, cascaded use can help project economics by shortening the payback period (Lund and Chiasson 2007). Cascaded systems are redundant because they draw from various multiple-well power plants for extraction of geothermal fluids, have various separation stations, and demonstrate aspects of recoverability (Brophy et al 2015; Ragnarsson et al. 2020). For example, the Hellisheidi power plant in Iceland feeds into a cascaded use system that can adjust for demand by fluctuating condenser pressure and water temperature (Hallgrímsdóttir et al. 2012). The cascaded use system in place in Reykjavik has 99.9%–100% reliability (Figure 7). However, it is difficult to quantify the resilience benefits from a single power plant as opposed to a cascaded use system holistically, representative of the limitations of determining the specifics of reliability of recoverability of CHP systems.

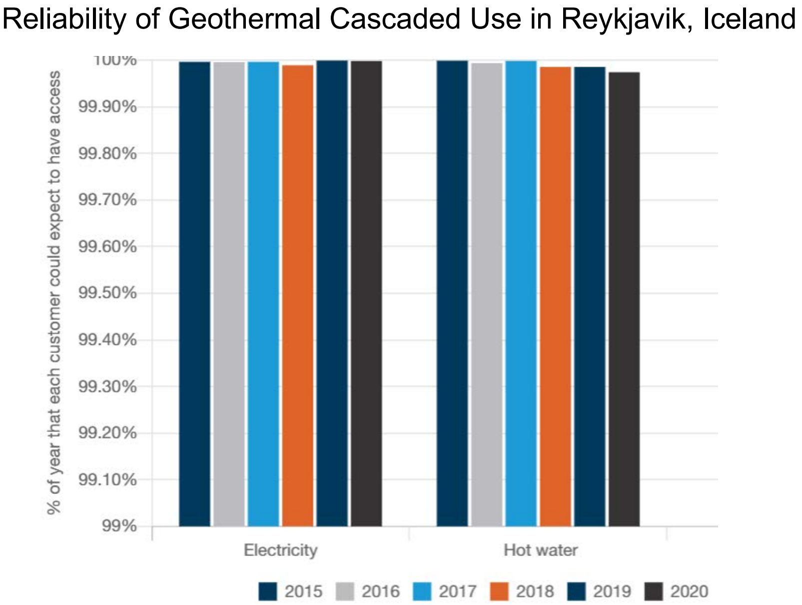


Figure 7. Reliability of geothermal cascaded use in Reykjavik, Iceland 2015–2020 (geothermal electricity and hot water)

Source: Reykjavik Energy, 2020

7. Discussion

7.1. Resilience of BAU Energy Systems in Arctic Countries

A true analysis of the energy resilience of "business as usual" (BAU) in Arctic countries is beyond the scope of this paper. Drawing from approaches that involve identification of threats and vulnerabilities, general statements can be made about the resilience of large-scale grids, microgrids, and heating systems in Arctic countries. In general, the majority of these energy systems appear to be under threat. Many of these threats are global in magnitude and difficult to mitigate (e.g., climate change). These threats increase the vulnerability of communities affected, who have very little power to reduce the large-scale threats. This is an environmental justice issue that touches on the very survival of communities in Arctic countries, because it affects so many other systems that are energy-dependent: food, infrastructure and housing, water, jobs, ecological health, and so on.

7.2. Resilience of Integrated Geothermal Energy Systems in Arctic Countries

Considering the resilience attributes of components of geothermal energy systems suggests that geothermal power, where available, has the potential to support the resilience of large-scale grids as well as microgrids in Arctic countries. Compared to other energy sources for large-scale utility grids, a theoretical geothermal-fired grid has many advantages across the resilience space, as indicated by the majority-green color-coded tables in the examples given previously. Disadvantages have to do with cost of installation, need for local education and a trained local workforce, and the susceptibility of geothermal to natural hazards related to volcanic eruptions and earthquakes. However, there are many unknowns because geothermal microgrids have not been widely deployed, and there are very few published case studies available. For example, grid services such as ramping capacity and other issues remain to be investigated. Microgrids in remote communities must adapt to the fact that loads change sometimes very quickly and unpredictably, and have different levels of importance and sensitivity (AEO 2020). Theoretically, geothermal microgrids can do this, meaning they have similar resilience advantages when compared to larger-scale utility grids, but that remains to be tested with increased deployment.

Even more striking is the resilient performance of geothermal heat. The Reykjavik GDH case study has an extremely resilient profile. When heat energy is considered as part of integrated energy systems in the Arctic, the resilience-enhancing qualities of geothermal energy become even more pronounced. However, it should be noted that the geothermal resources in Iceland are extremely high-grade and not geologically analogous to the types of geothermal resources found in any other Arctic country. Other regions in Arctic countries with high-grade resources include Kamchatka, Russia, the Kuril Islands, the Aleutian Islands in Alaska, and potentially parts of the Cascade Volcanic Belt in Canada and the United States.

7.3. Including Externalities in Resilience Considerations

As defined in Section 1.3.3, externalities are factors that are not accounted for in cost-based models and calculations, but are nonetheless important to the resilience in Arctic countries. Some externalities related to energy resilience in remote communities in Arctic countries are presented in Table 11, along with a proposed metric for internalizing impacts. Also listed are primary characteristics of those externalities in energy BAU and associated vulnerabilities, as well as characteristics of those externalities in geothermal energy alternative. Metrics for measuring the resilience impacts of these externalities are also proposed.

Table 11. List of Energy Resilience Externalities in *Remote Communities* in Arctic Countries

Arctic Energy Externality	Energy BAU	BAU Vulnerabilities	Geothermal Energy Alternative	Resilience Metric
Heat Security	Imported heating fuel	Short survivability in fuel supply chain disruptions in cold climates	Added survivability from locally produced heating	Hours/days of survivability
Food Security	Imported food	Supply chain disruptions impact imports	Locally produced food from clean greenhouses	Revenue from food sales and/or avoided costs of food purchases
	Subsistence food supplies under threat	Increased dependence on imports	Locally produced food from clean greenhouses	Days per year of access to fresh food
Energy Equity	High and/or fluctuating fuel prices	Affordability, dependence on associated state aid such as PCE in Alaska	Fixed energy prices	Avoided subsidies such as PCE
Power Security	Imported diesel fuel	Disruptions impact operation of facilities, communications, cold storage for food, etc.	Locally produced power	Hours/days of survivability
Job Security	Jobs: O&M on diesel gensets	Unknown, maybe none	Jobs: energy systems O&M (heat & power)	Number of jobs replaced
	Jobs related to fuel transport, storage, cleanup, etc.	Unknown, maybe none	Jobs related to food production and other economic opportunities from surplus heat	Number of jobs lost vs. created
Environmental Justice and Climate Justice	Climate change from fossil fuel combustion	Indigenous and remote communities face the worst consequences of climate change, but contribute little to its causes and are powerless to change them	Eliminating local sources of GHG emissions. Widespread deployment of geothermal energy could reduce worldwide GHG emissions	Cost of avoided emissions
Community Health	Fuel handling and emissions	Impacts of fuel handling and emissions on community	Eliminating fuel handling and local sources of GHG emissions	Costs and other measures of impacts on air, water, and land (e.g., reduction in contaminants)
Ecological Health	Imported heating and diesel fuel	Impacts of fuel transport, storage, distribution, combustion	Environmental benefits of eliminating fuel use	Emissions reductions plus other fuel-related costs (e.g., fuel spill cleanup)
Economic Development Opportunities	Few opportunities in remote communities	Opportunities are limited by energy prices, remoteness, and access issues	Tourism, agricultural and/or industrial use of process heat	Revenue or projected revenue from tourism, agricultural and/or industrial activities

Financial assistance for fuel transport, storage, and prices is intended to address energy inequity and energy insecurity. While this is intended to enhance community resilience, the practice may be doing the opposite by lowering other more fundamental aspects of community resilience, such as food security, ecological health, community health, environmental and climate justice, and economic development opportunities by entrenching BAU and impeding renewable energy development in these rural communities (Poelzer et al. 2016).

Some externalities related to energy resilience in grid-connected communities in Arctic countries are presented in Table 12, along with a proposed metric for internalizing impacts.

Table 12. List of Energy Resilience Externalities in *Grid-Connected Communities* in Arctic Countries

Arctic Energy Externality	Energy BAU	BAU Vulnerabilities	Geothermal Energy Alternative	Resilience Metric
Heat Security	Most DH run on imported heating fuel	Short survivability in fuel supply chain disruptions in cold climates	Added survivability from locally produced heating	Hours/days of survivability
Food Security	Imported food	Supply chain disruptions impact imports	Locally produced food from clean greenhouses	Revenue from food sales and/or avoided costs of food purchases
Energy Equity	High residential energy prices in compared to commercial and industrial users	Residents pay high prices	Fixed costs from PPAs and heat contracts for long-duration geothermal heat and power	Cost reduction/increase
Power Security	Coal-fired and hydroelectric grids dominate the north	Coal combustion is being highly taxed in most Arctic countries	Clean, locally produced power	Avoided cost of emissions, avoided O&M costs on hydroelectric plants (dams)
Job Security	Jobs from BAU heat and power systems (O&M, fuel transport, storage, etc.)	Unknown, maybe none	Jobs: energy systems O&M (heat & power) and related jobs (e.g., food production and other economic opportunities from surplus heat)	Number of jobs lost vs. created
Environmental Justice and Climate Justice	Climate change from fossil fuel combustion	Cities in Arctic countries face the worst consequences of climate change, but contribute little to its causes and are powerless to change them	Eliminating local sources of GHG emissions. Widespread deployment of geothermal energy could reduce worldwide GHG emissions	Cost of avoided emissions
Community Health	Fuel handling and emissions	Impacts of fuel handling and emissions (e.g., smog, ice fog) on community	Eliminating fuel handling and local sources of GHG emissions	Costs and other measures of impacts on air, water, and land (e.g., reduction in contaminants)
Ecological Health	Imported heating and diesel fuel	Impacts of fuel transport, storage, distribution, combustion	Environmental benefits of eliminating fuel use	Emissions reductions plus other fuel-related costs (e.g., fuel spill cleanup)
Economic Development Opportunities	Arctic countries have significant industrial activities, but opportunities linked to basic needs (e.g., food) are limited	Limited by climate, energy availability and prices, and other factors	Tourism, agricultural and/or industrial use of process heat	Revenue or projected revenue from tourism, agricultural and/or industrial activities

7.4. The Future of Energy in Arctic Countries

The economics of small-scale geothermal applications are a barrier to deployment today but are improving. Carbon pricing (such as taxes, cap-and-trade, and other accounting structures) has had a positive impact on geothermal energy deployment in countries where these policies have been implemented, including several Arctic countries. Geo-exchange technology was initially promoted and funded by the Swedish government following the fuel crisis of the 1970s (Gehlin et al. 2020). Today, subsidies are available for geo-exchange installation, and the country's carbon tax is the highest in the world. Since the implementation of the carbon tax, Sweden has reduced greenhouse gas emissions by 27% while maintaining GDP growth. Other Arctic countries are following suit. Norway also implemented a carbon tax in 1991, banned fossil fuel heating systems from new buildings in 2016, and is currently working to ban fossil fuels for all space heating (Midttømme et al. 2021). Canada implemented a carbon tax in 2019, with a carbon dividend system that returns the tax revenue to the province (Jonsson et al. 2020). Given these developments, many Arctic countries are projecting future growth in geothermal capacity (Table 13). Due to carbon pricing and other factors, GDH systems are rapidly being deployed in Europe. Until recently, GDH was limited to areas where geothermal resources above 30°C are located at relatively shallow, drillable depths, but this is changing. A pilot GDH project currently underway in Espoo, Finland, will use geothermal fluids from the deepest geothermal wells in the world (approximately 6 km), and similar Finnish geothermal projects may follow (Richter 2020). On the other hand, few new GDH systems have been installed in the United States since the 1980s, and Canada has no GDH installations, though one project initiated in 1979 in Saskatchewan was recently revitalized (Dale 2021).

Table 13. Current and Projected Geothermal Power Production in Arctic Nations

Sources: Huttrer (2020), and Robins, Kolker, and Espino (2021/in preparation)

Country	MWe	Forecast 2025 (MWe)
United States	3,700	4,313
Russia	82	96
Iceland	755	755
Greenland	0	0
Canada	0	10
Norway	0	0
Sweden	0	0
Finland	0	0
TOTALS	4,537	5,174

8. Conclusions

Energy systems in remote communities in Arctic countries can be viewed as integrated heat-power-food systems essential for community survival and resilience. Conventional energy systems in Arctic countries are susceptible to disruptions—both grid-connected and remote communities are likely to face continuing threats from severe weather events, supply chain disruptions, unstable and increasing diesel cost, etc. The question this paper seeks to answer is: are integrated geothermal energy systems resilient solutions for communities in Arctic countries? The answer appears to be yes. Geothermal is a resilient energy source for power and heat, and in turn, its use can enhance the resilience of communities in Arctic countries. This is true in smaller, isolated microgrid contexts as well. Although the economics of small-scale geothermal applications may remain a barrier today (though one that is getting smaller with each new technological advancement), from the perspective of technical viability, reliability, and sustainability, geothermal can play a significant role in providing resilient energy solutions to remote communities in areas where resources are present (see Figure 5). Notably, geothermal offers a known technology that is reliant only on locally occurring resources (and thus independent of outside fuel supplies) and can supply dispatchable and flexible baseload heat *and* power—a unique mix of characteristics that no other energy source can yet lay claim to. Limited deployment of geothermal microgrids in off-grid settings means that many unknowns remain about their performance, but the success of large grid-connected geothermal in providing ancillary services—particularly critical to microgrid operation—and the success of small geothermal in providing inexpensive power to remote communities are promising steps.

Suggestions for further work include refining our understanding of geothermal resources in Arctic countries and quantifying the value of energy resilience for both heat and power.

Glossary

Term	Definition
Ancillary services	Services that maintain a stable, consistent power grid. Ancillary services maintain the desired grid frequency and voltage. Typical examples of ancillary services include frequency regulation, voltage response, spinning and non-spinning reserves, and others.
Black start	The ability of a generator to support a grid coming back online after a blackout
Frequency	The frequency of the AC power waveform. Typical grid frequency is 60 Hz.
Islanded	A system that is connected to a larger grid but is able to temporarily "disconnect" and operate independently as a microgrid if/when necessary. For example, during grid failures a microgrid may switch to "islanded" mode and supply power only for local consumption.
Microgrids	A small, self-sustained electricity grid consisting of loads, generators, and various power electronics needed to form the grid. A microgrid may be connected to another grid, or islanded.
Ramping	A generator increasing (ramping up) or decreasing (ramping down) its power output, typically in response to changes in load or output of other generators on the system.

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