Geothermal Energy and Resilience in Arctic Countries

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ABSTRACT

The eight Arctic countries have diverse energy systems but can be split into two distinct groups based on energy characteristics. The first group includes countries which are heavily grid-connected (Iceland, Norway, Sweden, and Finland); the second group includes countries with some grids as well as an abundance of remote microgrids, particularly in their more northern regions (Canada, Russia, the United States [Alaska], and Greenland). The primary energy source for both heat and power in remote communities is almost exclusively diesel.

Geothermal energy is currently used in all eight Arctic countries, providing heat and sometimes electricity at utility scales and at the microgrid scale. However, the availability of geothermal resources is poorly defined in Arctic countries. We reframe geothermal heat and power as integrated energy systems, asking the question: are integrated geothermal energy systems—where available and economic—resilient solutions for communities in Arctic countries? Resilience attributes of integrated geothermal energy systems are identified, with a focus on microgrids and small-scale applications.

1. Introduction

Energy systems in Arctic countries are in transition. The eight Arctic countries, defined as members of the Arctic Council, include Iceland, Canada, Greenland, Norway, Sweden, Finland, Russia, and the United States. Arctic countries are particularly vulnerable to climate change and other related changes (e.g., geopolitical), which can cause disruptions to energy systems and their support infrastructure. Due to the remoteness of many communities in Arctic countries, it is challenging to recover from natural disasters, which are increasing in frequency and magnitude.

Resilience is defined many ways. Resilience is a broad topic that simply asks the question, “is the system, component, community, etc. prepared to handle a major disruption?” We use the following definition from Hotchkiss and Dane (2019): *Resilience is the ability to anticipate, prepare for, and adapt to changing conditions and withstand, respond to, and recover rapidly from disruptions.* Establishing methods and metrics for quantifying or valuing energy resilience is an active area of research. Much attention has been paid to the resilience of the electric grid, focusing on preventing power disruption and, when an outage does occur, restoring electricity supply as quickly as possible while mitigating the consequences (Anderson et al. 2017).

Because resilience is often 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). Qualitative metrics based on those five attributes of resilience will be used in this paper.

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 resilience, reframing energy systems within the context of other important components of a healthy community—access to food, housing, energy, infrastructure, and economic development (Bahnke et al. 2020). Integrated energy systems utilizing geothermal heat and power could be a resilient energy solution for communities in Arctic countries. 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 corresponding risks of supply chain disruption.
2. **A high capacity factor**: this makes geothermal energy more comparable to fossil fuel power plants than variable renewable energy technologies.
3. **Long lifetime:** geothermal energy can include provide baseload heat and power for several decades and in some cases for centuries.
4. **Low operational costs:** geothermal energy installations have relatively high capital costs, but low operational costs.
5. **Load flexibility:** while not standard practice, geothermal power plant loads can technically be increased or decreased relative to demand (Geirdal 2015).

Geothermal energy also has many ancillary benefits to its users, including: (1) low greenhouse gas **emissions** and **small environmental footprint (**low land use per unit of energy produced); (2) supply of both heat and power (when available and designed to do so), thus providing

economic development and food security opportunities to remote communities otherwise dependent on imported food; and (3) increased **energy security** due to local, baseload supply.

2. Energy Use in Arctic Countries

Arctic countries have diverse energy systems. Many communities in Arctic countries are small and remote. These remote communities are rarely connected to a larger energy grid and must supply their energy locally, typically via fossil fuels (e.g., diesel, natural gas, and coal) (de Witt et al. 2019). Small local electrical generation systems are called microgrids. A microgrid can either be attached to a centralized grid or operate independently in “island-mode” (unconnected to a grid, or connected to a grid but able to temporarily disconnect and operate independently; Anderson et al. 2017). In Russia, Greenland, Canada, and the United States (Alaska), microgrids are prevalent, serving loads ranging in size from a single building to an entire community. Diesel fuel provides power and heating for remote microgrids, usually imported via barge in the summer months.

The Nordic countries—Iceland, Norway, Sweden, and Finland—have national grids supplying power to nearly all residents. Iceland and Norway are exceptions in Arctic countries, with almost 100% renewable energy sources (Norway’s grids are primarily powered by hydroelectric, and Iceland’s grids are powered by a mix of geothermal and hydroelectric). National grids in Sweden and Finland are powered by a mix of hydroelectric, coal, nuclear, and hydrocarbons. In those countries, energy challenges are related to meeting aggressive carbon emission reduction targets. Sweden and Finland have two of the most rigorous carbon pricing laws in the world.

The pan-Arctic map in Figure 1 shows the locations of power generation facilities, grouped by primary fuel type. 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 2021; Fig. 6). In Iceland, geothermal heat district heating systems are prevalent (Richter 2016).

2.1 Energy resilience in Arctic countries

2.1.1 Threats and vulnerabilities related to energy systems in Arctic countries

The simplified energy supply chain into Arctic countries includes transportation, storage, distribution, conversion, combustion, transmission, and consumption. Each of the links in this supply chain encompasses one or more major disruption threats to communities, causing vulnerability (lack of resilience). The impact of disruptions on remote communities is usually limited to the community itself, but it can be catastrophic. Some examples of vulnerabilities in remote energy systems include: aging technology and lack of operations and maintenance (O&M) funding (Schaeffer et al. 2018), lack of a local trained workforce, seasonality of fuel delivery (Arctic Energy Office [AEO], 2020), coupled with increasingly severe weather threats. Grid-connected energy systems are susceptible to failure from both natural and human-caused disruptions, but recovery can be easier than with remote systems.

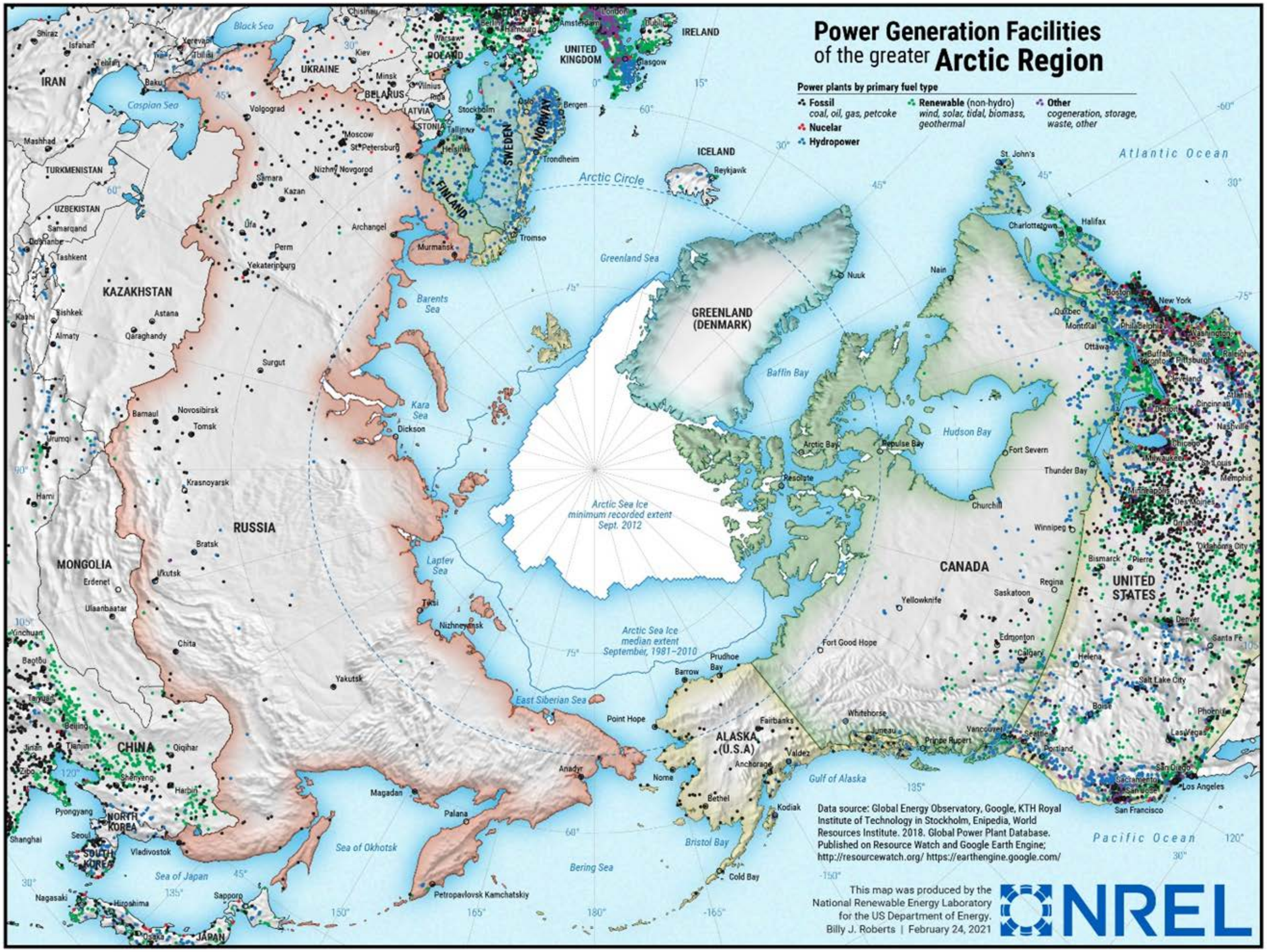

Figure 1. A pan-arctic view of power generation facilities showing power plants by primary fuel type. Map credit: Billy Roberts, NREL.

A key vulnerability of energy systems in Arctic countries is the life-or-death requirement of heat during cold winters. In Scandinavian countries, district heating systems are linked to electrical power grids. Those grids thus serve simultaneous peak electrical and heating loads in winter, requiring supplemental fuel imports (Laine 2017). Cost of energy is another key vulnerability. In Alaska, rural communities face electricity costs three to five times higher than the rest of the state (Brinkman et al. 2014; Fay et al. 2013; Thayer 2019). Alaska's Power Cost Equalization (PCE) program subsidizes cost of fuel for the first 500 kWh/month (Holdmann and Asmus 2019); but the PCE budget is partially linked to petroleum revenues and therefore variable.

2.1.1 Energy costs in Arctic countries

Energy costs are highly variable in Arctic countries (Table 1). The majority of remote communities are dependent on diesel, resulting in high heat and power costs (Holdmann and Asmus 2019; AEO 2020). Governments sometimes provide financial assistance for both heat and power costs, which can decrease costs of electricity generation by an average of 65¢/kWh (Izhbuldin and Dobrovolskaya 2019; Lovekin et al. 2016; Chade et al. 2015; Poelzer et al. 2016).

Table 1. Average Cost of Power and Heat (2011-2020) in Arctic Countries, in USD¢/kWh

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							

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).

2.2 Renewable energy use in Arctic countries

In 2021, the use of diesel fuel is increasingly being viewed in terms of both financial and environmental costs. 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. Concerns about environmental and health impacts of widespread diesel fuel use are becoming internalized into energy planning decisions. The benefits of grid-connected renewable-based microgrids include offsetting bulk energy purchases, reducing peak demand, performing energy arbitrage, and providing ancillary services. These same systems can be islanded to form a microgrid, along with diesel generators (Anderson et al. 2017). The combination of threats to diesel fuel supply, increased cost-effectiveness of renewable energy systems, and carbon pricing in some Arctic countries has generated significant interest in using renewable energy technologies.

The most widely used renewable energy technology in Arctic countries is hydroelectric power. Some smaller-scale communities in Iceland, Canada, the United States, and Greenland have access to hydropower, but high capital costs make it difficult for most remote microgrid communities. Coastal Alaskan communities have been integrating wind into their microgrids (de Witt et al. 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, with geothermal energy accounting for 62% of total Icelandic energy production (Huttrer 2020).

2.2 Geothermal energy use in Arctic countries

2.2.1 Types of geothermal energy use in Arctic countries

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 the Candaian Geothermal Energy Association, 2016):

(1) **Geo-exchange** (<30°C)

(2) **Direct use** of geothermal heat (30°C–150°C)

(3) **Geothermal power** (>80°C)

The availability of geothermal resources is poorly understood in most of the Arctic countries, with the exception of Iceland. A pan-Arctic geothermal resource map is shown in Figure 2. In this map, geothermal resources are grouped by the *type of applications that can likely be achieved* based on what is known about the subsurface. Also shown on this map are the locations of geothermal power plants in the Arctic countries (data courtesy of Richter [2021]).

2.2.2 Use of geo-exchange in Arctic countries

Geo-exchange, also known as geothermal or ground-source heat pump technology, is used in residential/commercial space heating and cooling applications with the use of a heat pump and tubing at shallow depths. Geothermal heat pumps (GHPs) can function in regions of Arctic countries that are free of continuous permafrost; however, there is limited research on their long-term performance in extremely cold environments (Meyer et al. 2011). Sweden is a world leader in geo-exchange deployment, with more than 500,000 geo-exchange systems installed for space heating and domestic hot water heating, and 6,680 MWth of installed heating capacity (Gehlin et al. 2020). A geo-exchange-based district heating system in the city of Lund has been functioning since 1985 (Aldenius 2019). Geo-exchange technology is also widely used in other Scandinavian countries. Finland has 140,000 geo-exchange systems (Kallio 2019) and Norway has 60,000 geo-exchange systems (Midttømme et al. 2021). Sweden's higher usage of geo-exchange compared with neighboring countries can be explained by policy differences (Hirvonen 2017). The majority of the geo-exchange systems in these countries are not in subarctic or Arctic regions.

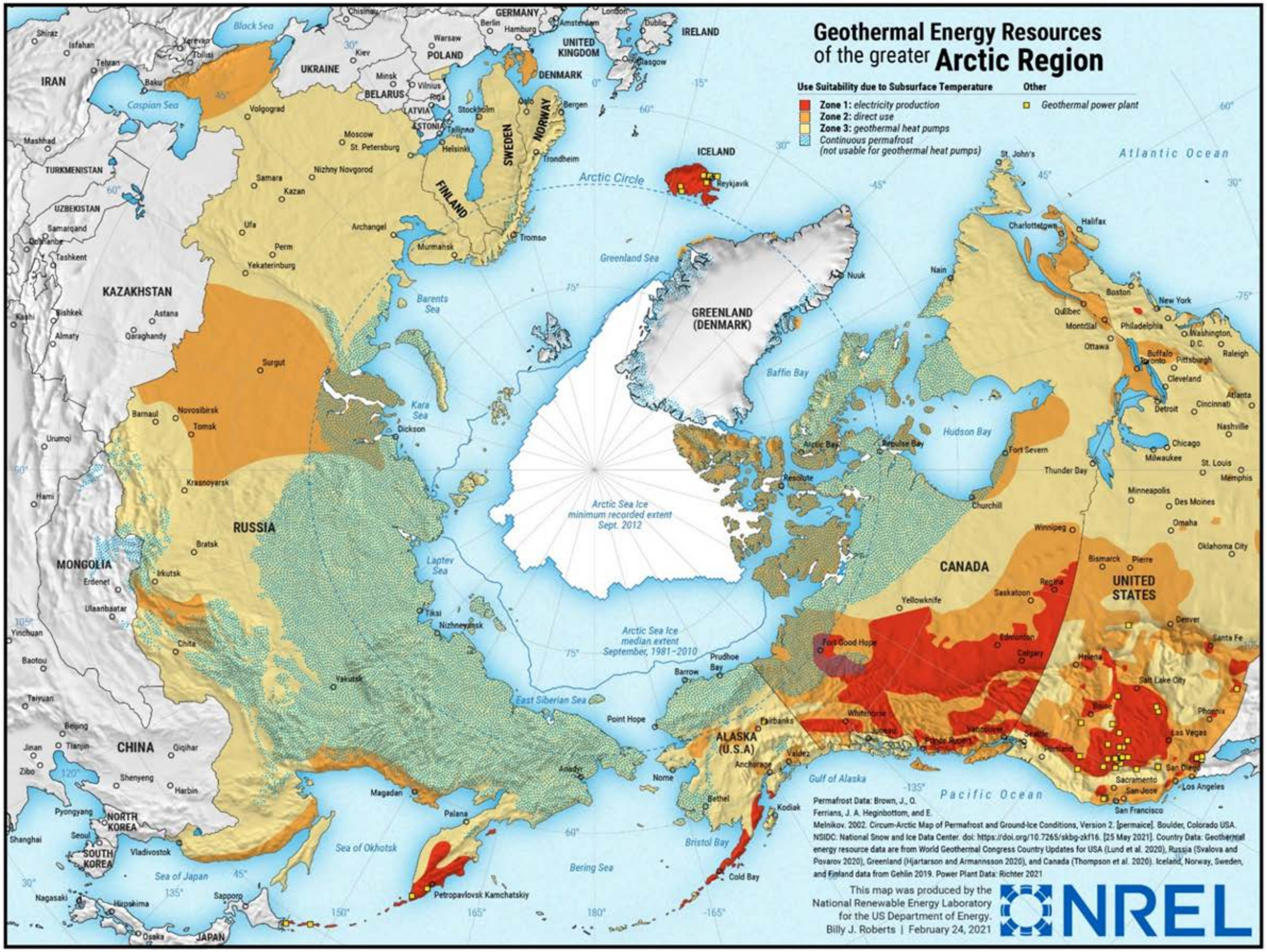

Figure 2. General geothermal energy resources by utilization type, and locations of geothermal power plants, in the Arctic countries. Map credit: Billy Roberts, NREL. Power plant data from Richter (2021). Baseline subsurface data for this map come from a wide variety of sources and vary in quality.

2.2.3 Direct use of geothermal heat in Arctic countries

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). 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 USA 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 (Hjartarson and Armannsson 2020; Thompson et al. 2020). Geothermal district heating (GDH) is favorable in cold climates due to a higher load factor (Lund and Toth 2021). GDH systems can utilize 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). GDH accounts for the following percentages of geothermal direct use in Arctic countries: approximately 90% in Iceland (Orkustofnun 2019), 19% in the United States, and 26% in Russia (calculated from Lund and Toth 2021). Iceland has about 230 GDH systems. The United States has 23 GDH systems (Robins et al. in preparation), and Russia has seven GDH systems (Lund and Toth 2020), but only one is located in subarctic (the region immediately south of the Arctic Circle) or Arctic regions.

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 (calculated from Huttrer [2020] and Ragnarsson et al. [2020]).

2.2.4 Use of geothermal electricity in Arctic countries

Three out of the eight Arctic countries have geothermal power plants: Iceland, the United States, and Russia. The United States has the greatest installed geothermal capacity worldwide at 3700 MWe from 99 power plants (Huttrer 2020) but only one is located in a subarctic climate. 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; Fig. 2). Table 2 summarizes the geothermal energy use in the eight 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). This extremely wide range is due to a combination of technical, resource, and socio-political factors.

3. Resilience of Geothermal Energy

To evaluate the resilience of utility-scale and microgrid scale geothermal power systems, as well as geothermal district heating systems, we selected three case studies from Arctic countries. Not all of the case studies are located in Arctic or subarctic regions. The following case studies focus on present performance of geothermal energy installations and not on costs. Historical issues are mentioned but not evaluated in detail.

Table 2. 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 8 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	No data	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**	**4537**	**484**	**3,280**	**17,650,126**	**32,300**

3.1 Resilience of geothermal electricity

Geothermal energy serves as a baseload resource for many electrical grids worldwide (Brophy et al. 2015; Lund and Toth 2021). While use of geothermal power reduces costs and emissions from 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 most cases, diesel generation is integral to the formation of the grid. In Russia, the Pauzhetka geothermal 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. At some sites, the system is redundant and capable of controlling grid frequency, black-start (the ability to restart the grid in the case of a blackout), and handling various operational conditions (Hardarson et al. 2018). Note that a diesel generator or grid connection is needed to black-start a geothermal plant with pumped wells.

Grid-connected geothermal power is a widely proven technology. Although geothermal can be unstable in low-load operation, this can be mitigated with storage, capacitors, and other technologies. 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. Geothermal can recover from external events: it is minimally 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.

Though geothermal systems can provide ancillary services to stabilize the grid, this is not widely implemented, likely due to the lack of incentive to provide such services (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 short-timescale operation. Edmunds et al. (2014) proposed using reservoir management to compensate for imbalances between grid load and generation.

3.1.1 Case study on the resilience of a utility-scale geothermal power plant

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. A volcanic eruption in 2018 forced the plant offline 2018-2020. Flexible operation has not increased the plant's O&M costs. The plant consists of ten 3-MWe modular geothermal combined cycle units (GCCUs) in addition to two binary cycle bottoming organic rankine cycle (ORC) units that increase the capacity by 8 MWe. PGV engages in frequency and voltage response (Matek 2015). The plant is dispatchable between 22 and 38 MWe, it can perform a 2-MWe/min ramp with an additional quick load pick up of 3-MWe 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 such, the plant can provide spinning reserve, frequency response, and voltage response. When demand 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 required net power, grid frequency, and grid voltage to the control system, which responds with current spinning reserve, current upper limit for available dispatch, and current lower limit for available dispatch, allowing PGV to automatically adjust its power output according to grid needs. The PGV system is redundant in that only nine of ten GCCUs are needed for full capacity, so one at a time can be offline for maintenance without reducing output (Nordquist et al. 2013). Table 3 evaluates key components of PGV with respect to resilience attributes.

PGV enhances the resilience of the Hawai'ian grid in several ways. The redundant system allows the plant to maintain full operation during maintenance or a module fault. It is not dependent on fuel imports, is immune to extreme weather in the Pacific, provides ancillary services to the grid, and has the technical potential to support black-start. Also, the flexibility of the plant allows for greater penetration of variable renewable resources onto the grid. On the other hand, the PGV is susceptible to volcanic eruptions, one of which forced the plant offline 2018-2020. It should be noted that this is rare: while many geothermal power plants are located near volcanoes, very few have had operations affected by volcanic eruptions.

3.1.2 Resilience of 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.

Table 3. Resilience of Key System Components for the 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

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, while 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.

3.1.3 Case study on the resilience of a microgrid-scale geothermal power plant

A 680-kWe isolated hybrid geothermal-diesel microgrid has been operating in Chena Hot Springs, Alaska (CHS) since 2006. The power plant utilizes the lowest-temperature geothermal electricity source in the world, at 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 (Holdmann 2007). Hot fluids are cascaded from the power plant and used for district heating, greenhouses, a spa, and other uses (such as seasonal cooling via an absorption chiller that runs on geothermal heat; Erickson and Holdmann 2005). The addition of multiple geothermal units further increased the redundance of the system. The original, custom-built ORC units had maintenance issues and were ultimately replaced with mass-produced generators. Overall, the plant has operated successfully, with modifications related to the geothermal supply, the cold-water supply, and the injection scheme. Table 4 evaluates key components of CHS with respect to resilience attributes.

3.2 Resilience of geothermal heat

Thermal energy—heat—is a matter of survival in many Arctic and subarctic communities. Evaluating resilience as an attribute of an integrated geothermal energy system (heat and power) 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. NREL used resilience metrics for geothermal district heating systems based on the attributes defined for electrical energy systems (Table 5).

Table 4. Resilience of Key System Components for 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. Small systems with slimholes require smaller equipment
	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

3.2.1 Case study on the resilience of geothermal district heating

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 5.

Table 5. Resilience of Key System Components for the Geothermal District Heating System in Reykjavik, Iceland (RGDH). Green: RGDH excels; yellow: RGDH is average; orange: RGDH performs poorly.

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

3.2.2 Resilience of geothermal cascaded use systems

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 3).

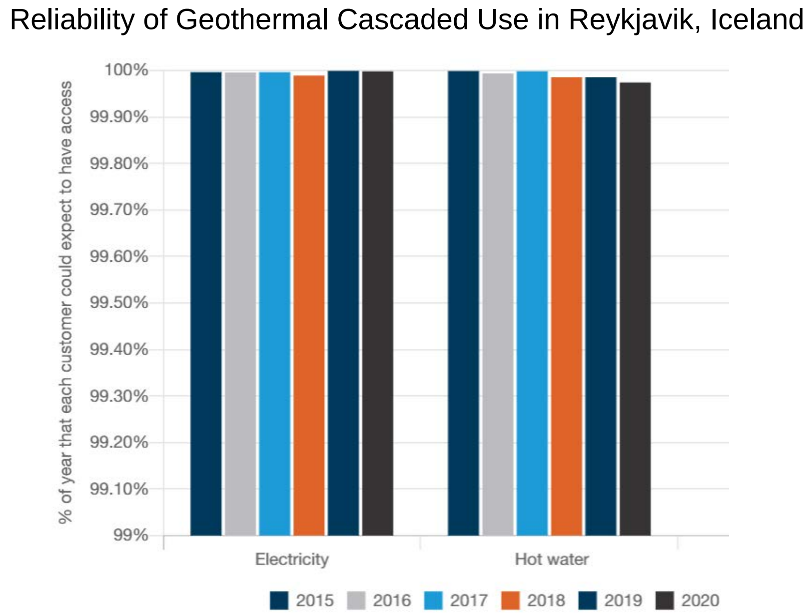

Figure 3. Reliability of geothermal cascaded use in Reykjavik, Iceland 2015-2020 (geothermal electricity and hot water). Source: Reykjavik Energy, 2020.

4. Discussion

4.1 Resilience of business-as-usual compared to geothermal energy systems in Arctic countries

The resilience of some large-scale grids, as well as microgrids and heating systems in Arctic countries appear to be under threat. Some 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 little power to reduce them. This environmental justice issue 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.

Evaluating 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, a geothermal grid has many resilience-related advantages, as indicated by the majority-green color-coded Tables 3-5. Disadvantages include cost of installation, need for local education and a trained local workforce, and the susceptibility of geothermal installations 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. Microgrids in remote communities must adapt to the fact that loads sometimes change quickly and unpredictably and have different levels of importance and sensitivity (AEO 2020). Theoretically, geothermal microgrids can do this, but that remains to be tested.

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.

4.2 The future of geothermal 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).

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, dormant for decades, was recently revitalized. That project is planning a GDH demonstration project (Dale 2021).

5. Conclusions and Future Work

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 in the cost of diesel, 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 grid-connected and remote communities in Arctic countries.

The economics of small-scale geothermal applications are a barrier today, especially when the attributes of resilience are hard to monetize. 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 resilience for both heat and power, particularly in Arctic countries.

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