Mapping Hot Water Bleeding in District Heating Systems: Characterizing and Untapped Source of Thermal Energy

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Abstract

Iceland's location on the Mid-Atlantic ridge creates a large geothermal potential – one which Iceland harnesses for energy production and heating. Geothermal district heating systems distribute heat in the form of hot water or steam. To maintain adequate water pressure and temperature at destinations far from the heat source, heated water is released at a hot water bleed location. While data show that this water is often around 50°C, a lack of research on these hot water bleeds and the amount of thermal energy potential is a barrier to reuse of this thermal energy. Hot water bleed data from Northern Iceland was compiled to understand the scale at which this thermal energy is available and the seasonal availability. Mapping tools were used to visualize water temperature, flow, and thermal energy of these sites to understand the feasibility and optimal locations for use. Total heat use data was compared with energy producers across Iceland, placing our findings in a national context and predicting the potential of thermal energy from hot water bleeds at a large scale. Results highlight several optimal locations within Skagafjördur to consider for hot water bleed reuse projects. Calculations determined that there is sufficient thermal energy for heating moderately sized greenhouses and pilot aquaculture farms. The maps assist in understanding where bleed sites are capable of combined use to increase the amount of total thermal energy available. Higher thermal energy output in the summer and lower output during the winter indicate that seasonality is an important consideration when determining thermal energy reliability throughout the year. These findings demonstrate a potential for energy producers to increase the efficiency and benefits of their services. The graphs and maps produced in this study are tools to visualize the availability of thermal energy within Northern Iceland. If a site is chosen for a thermal energy reuse project, more extensive research on the location, feasibility, and ethics is required to determine optimal use.

Acknowledgements

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1. Introduction

1.1 Iceland's Geothermal Geology and History

Iceland is located along the Mid-Atlantic ridge at the boundary of the North American and Eurasian tectonic plates. Its volcanic nature is due to its location on a hot spot, where upwellings of hot material from the mantle melt the crust to create magma, leading to volcanic activity at the surface (Sleep, 1992). A volcanic zone runs across the country along the tectonic plate boundary. Within this zone exist more than 200 volcanoes and associated geothermal systems which are created largely by rainwater that has sunk below Earth's surface and been heated by hot substrata and magma intrusions (Gunnlaugsson & Ívarsson, 2010) (Ragnarsson et al., 2023). These geothermal systems range in composition as well as temperature from warm to supercritical. At least 25 high-temperature systems (> 200°C) and about 250 low-temperature systems (< 150 °C) have been identified (Ragnarsson et al., 2023).

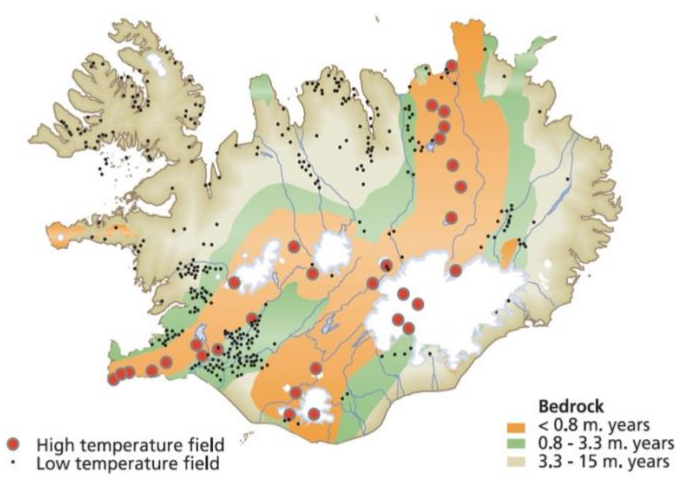

Figure 1. *Map depicting the distribution of high and low temperature geothermal systems in Iceland. The land is colorized to depict bedrock age in millions of years. (Gunnlaugsson & Ívarsson, 2010)*.

Iceland's geothermal energy potential remained largely untapped until the 1930s, when the first district heating system using geothermal water was installed in Reykjavík. Currently, 97% of Iceland's total heat is sourced from geothermal energy. The rest are indirectly heated using electricity or oil (Orkustofnun, 2024).

1.2 Harnessing Geothermal Energy at Different Temperatures

Geothermal energy can be harnessed with various methods and utilized across many sectors. Broadly, geothermal energy use falls into two categories: indirect and direct use. Indirect use involves using high-temperature geothermal brine -- typically above 150°C -- to generate steam and produce electricity (Gunnlaugsson & Ívarsson, 2010). Currently, almost 30% of Iceland's electricity is produced from indirect use, with the other 70% produced from hydroelectric systems (Orkustofnun, *2024*). Direct use, the subject of this study, involves the immediate use of lower-temperature geothermal energy (below 150°C) in the form of hot water or steam in a heating system. (*GEOTHERMAL POWER GENERATION*, 2007) (Dillman, 2018) (Gunnlaugsson & Ívarsson, 2010).

The temperature of geothermal energy determines its application in direct use. The Lindal Diagram, which indicates the ideal temperature range for various direct uses, aids in understanding the most profitable and efficient use of geothermal fluid (Gunnlaugsson & Ívarsson, 2010) (Dillman, 2018). The Lindal Diagram pictured in Fig.2 includes select utilizations relevant to this study.

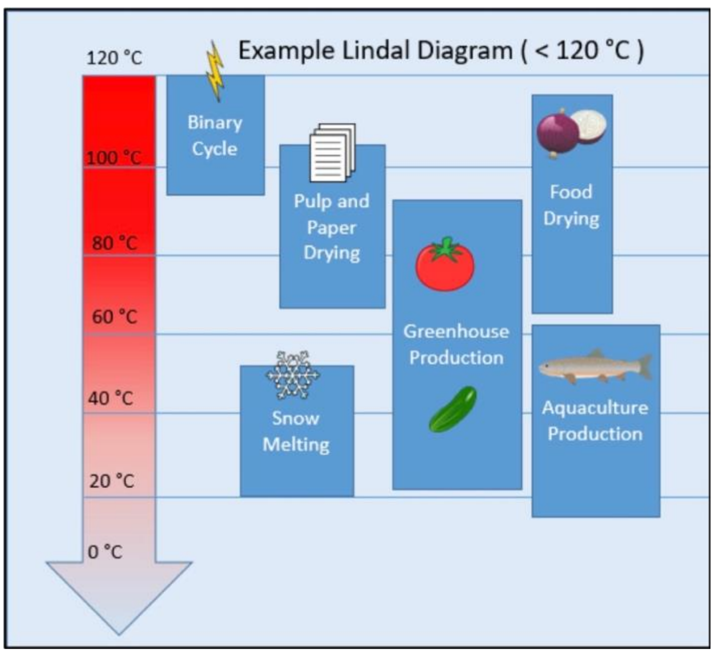

Figure 2. Lindal diagram for select geothermal utilization areas. Temperature is shown on the vertical axis and temperature ranges for each utilization are displayed. Particularly relevant to this study are utilizations for greenhouse and aquaculture production (Dillman, 2018).

Low-temperature geothermal energy is used primarily for heating purposes such as houses, greenhouses, aquaculture, pools, and snowmelt (*GEOTHERMAL POWER GENERATION*, 2007) (Dillman, 2018). In particular, agriculture and aquaculture can be heated at a lower temperature range where there is an abundance of geothermal resources, making them particularly attractive for this purpose (Gunnlaugsson & Ívarsson, 2010). For all forms of utilization, the presence of an adequate amount of thermal energy is a critical factor in determining if a hot water bleed location can be considered for a project that would put the unused thermal energy to use. A location's suitability is also determined by various additional factors that depend on the desired form of utilization.

One common use of lower-temperature geothermal energy are greenhouses. With a rapidly increasing world population, greenhouses are becoming an increasingly viable solution to meet the need for a significant increase in overall food production. They have the ability to produce 20 to 30 times as much produce than the same sized field production (Thomas et al., 2017). Greenhouses maximize crop yields by providing a controlled environment that allows efficiently grown, high quality produce while also being resilient to unpredictable climate conditions (Baeza et al., 2021). They are particularly useful in Iceland where the cold environment makes it difficult or impossible to grow crops year-round. This makes them an integral part of the Icelandic food system (Dillman, 2018). Approximately 40% of Iceland's fresh vegetables are grown within the country. The other 60% is imported, a more costly and environmentally taxing process (Halldórsdóttir & Nicholas, 2016). Of vegetables grown in Iceland, tomatoes and cucumbers are the majority of greenhouse yields (Butrico, 2018). Tomatoes in particular are effective for greenhouse cultivation due to their space and time efficiency, suitability for soilless cultivation, and their high tolerance to pests and diseases (Baeza et al., 2021).

A greenhouse's thermal energy use highly depends on location, construction materials, and crop parameters. Analysis of these factors that influence heat demand allow estimations of energy requirements (Table 1) to be calculated (Dillman, 2018).

Estimated Energy Requirement of a Tomato Greenhouse	
Energy for Heating (W/m^2)	Energy for Heating $(kWh/yr/m^2)$
234	2050

Table 1. The energy requirement per square meter of a tomato greenhouse using estimations from Dillman, 2018.

Another use for low-temperature thermal energy is aquaculture, also known as fish farming. In Iceland, Arctic char and cod are the dominant cultured species. Aquaculture is a form of fish production that has become popular as overfishing and climate change cause increasing pressure on the world's oceans. The vast majority of aquaculture is for the purpose of human consumption, although it is also use to restock rivers, lakes, and other bodies of water (Paisley et al., 2010). While not essential for fish farming, geothermal energy can increase fish farm yield in cooler climates like Iceland by reducing temperature fluctuations and optimizing the temperature for fish growth. Iceland is the world's largest exporter of Arctic Char (Salvelinus alpinus), a species conditioned for cooler climates, and Dillman's thesis focuses on the requirements for Arctic Char fish farms. Optimal growth temperatures for Arctic Char along with estimations for thermal energy use by outdoor inland Arctic Char farms sourced from Dillman are used as the thermal energy requirements (Table 2).

Estimated Energy Requirement of Arctic Char Aquaculture	
Energy (W/m^3)	Energy (kWh/yr per m^3)
556	4,870

Table 2. The energy requirement per cubic meter of a land-based outdoor Arctic Char fish farm (Dillman, 2018).

1.3 Geothermal District Heating Systems

Unlike conventional heating systems that generate heat on-site, geothermal district heating systems source hot water or steam from central geothermal well fields and distribute it to the desired location through a network of pipes (Gunnlaugsson & Ívarsson, 2010). A challenge arises in providing rural locations with hot water because it must travel through extensive lengths of pipes while also ensuring that it remains an adequate temperature and pressure for use. To maintain an adequate flow that minimizes the amount of heat lost during travel, hot water from the pipes can be released at the destination to create a pressure drop. This process is called hot water bleeding (Ottó Elíasson, personal communication). At hot water bleed locations, the heated water, often at temperatures around 50°C (Norðurorka, 2025), becomes a source of unused thermal energy.

1.4 Maximizing the Potential of Thermal Energy in District Heating Systems

Currently, these sources of unused thermal energy are largely unrecognized and unstudied throughout Iceland. Without research on hot water bleeds, it is impossible to know the scale of the problem, as well as if these locations are a viable and stable source of thermal energy. Comparisons of heat use data between Norðurorka and other energy producers in Iceland will allow us to understand the relative scale of our data as well as make predictions of what hot water bleed data may look like on a national scale. Within the bounds of the hot water bleed data in Skagafjördur and Eyjafjördur, visual mapping tools and analysis of total and seasonal hot water bleed trends will help determine where the most thermal energy loss occurs due to hot water bleeds within the district heating system. Once these locations are identified, using thermal energy requirements for greenhouses and aquaculture will allow us to understand the scale at which this unused thermal energy is available.

2. Methods

Data for this project were obtained from three sources in three formats. The first set of data was from the Orkustofnun, the Icelandic National Energy Authority which operates under the authority of the Ministry of the Environment, Energy, and Climate. Orkustofnun receives data on energy sources from the National Energy Authority. These datasheets included data compiled from energy producers across Iceland and aim to understand heat and energy production and use on a national scale. Data on total heat energy used in Iceland were sourced from the data sheet “Final Heat Use in Iceland 2023 by District Heating Area”.

The second set of data was from the Skagafjördur region located in Northern Iceland. Within Skagafjördur, data came from nine different municipalities and 57 different locations. Measurements were read manually at each site, once in 2024 and once in 2025. In 2024, depending on the location, the measurements were taken on May 1st, June 1st, or July 1st-5th. In 2025, measurements were read on February 1st-5th or June 1st depending on the location. The minimum difference in days between 2024 and 2025 measurements was 216 days; the largest was 396 days. The key measurements included cumulative outflow volume, water temperature, the collection date, and the coordinate location.

The final set of data was from Norðurorka, a utility company that provides services to Northern Iceland in the Eyjafjördur region just east of Skagafjordur. Norðurorka’s metering system collects time-stamped data on hot water bleed points within the district heating system. These data include measurements from 80 outflow locations between October 30, 2024, and October 30, 2025. The frequency of site measurements varied by between 1 and 8,769 measurements within the year period. The key components for this study were the collection date, cumulative volume of bleed outflow, water temperature, and coordinate location.

2.1 Treatment of National Data

Data from Orkustofnun B (Table 1) was used to create bar plots coded in R (R Core Team, 2023). The largest energy producers in Iceland, referred to as Main Activity Producers (MAP), were placed on the horizontal axis and the amount of heat they used in 2023 was placed on the vertical axis (Dr. Alessandra Schnider). The height of the bar represented the total heat use and different color divisions within each bar represented the various sectors that this heat was used for, as labeled in the legend. A second bar plot following the same structure as stated above but with the highest MAP user of heat (Veitur ohf.) removed was generated (Dr. Alessandra Schnider) to provide a clearer visual on the remaining MAPs.

2.2 Treatment of Skagafjördur and Norðurorka Data

The goal of the second section of analysis was to characterize hot water bleed locations by water temperature measurements as well as flow and thermal energy calculations. These data would be used to create a visual of the characteristics of hot water bleeds across Eyjafjördur, the region that Norðurorka services, and Skagafjördur. Because the data from Skagafjördur and Eyjafjördur were in different formats, they had to be standardized in order to compare them across the regions.

In Skagafjördur, the temperature at each bleed location was represented by a single temperature measurement. For each site, the annual volumetric flow, f_v was calculated using the difference in volume and days between the 2024 and 2025 measurements. Thermal energy was calculated in a few steps, first by finding the mass flow using the equation,

$$f_m = f_v \times \rho \tag{1}$$

where f_m is the mass flow rate, f_v is the volumetric flow rate, and $\rho = 1000 kg/m^3$ is used as the density of water. Then, the thermal power was calculated using the equation,

$$P = f_m * c_p * (T_{in} - T_{out}) \tag{2}$$

where P is thermal power, $c_p = 4{,}186\, J/kg$°C is the specific heat capacity, T_{in} is water temperature measured in the pipe, and $T_{out} = 15$°C is used as the water temperature after use. Finally, the thermal energy was calculated using the equation,

$$\mathrm{Q} = P * t_{hours} \tag{3}$$

Where Q is the thermal energy, P is the thermal power from (2), and t_{hours} is the number of hours in a year.

To characterize data in Eyjafjördur using the Norðurorka data, hot water bleed locations with less than two data points were first removed because the following flow calculations could not be done from a single data point. This left 59 locations that could be analyzed. The annual flow in both liters per second and cubic meters per hour was calculate using the difference in volume and days between the very first and very last measurement taken at each site. The temperature was represented using the mean temperature across the data collection period at each bleed location. Thermal energy was calculated as had been for the data from Skagafjördur using the volumetric flow and temperature using (1), (2), and (3) as described above.

Three separate maps for temperature, flow, and thermal energy were made to visualize the data across Skagafjördur and Eyjafjördur. The GIS mapping was done using Quantum Geographic Information System, Long Term Release (QGIS-LTR), a free open-source software for geospatial information visualization. The base layer for all the maps was the Open Street Map XYZ tile. The desired data was written into delimited text layers and placed on the map according to coordinate values. Graduated size and color classifications were used to visualize variations in data values.

The locations with the top five highest thermal energy values in Skagafjördur and Eyjafjördur were selected for more detailed analysis. The feasibility of implementing a specific use for the thermal energy can be put into context based using calculations for example utilizations. For each location, estimations of the size a tomato greenhouse or an Arctic char fish farm were calculated using the respective thermal energy requirements provided by Dillman, 2018. A satellite layer from Google Earth was used to analyze the location and infrastructure around each location. The location of each hot water bleed site within the district heating system network was noted.

For a more general characterization of these hot water bleeds to characterize each region and the regional data as a whole, simple calculations of average flow, temperature, and thermal energy as well as total thermal energy calculations were made in Microsoft Excel. This was done by averaging or summing the respective values over the time period of data collection.

2.3 Treatment of Time-Based Data

The third section of the study consisted of a seasonal variability analysis of Norðurorka's data to determine how water temperature, flow, and thermal energy change seasonally. To provide a clear seasonal trend, each of these characteristics within the data were grouped and averaged by month to account for inconsistent or incomplete data collection at some locations. Days that included multiple measurements were consolidated into one measurement per day, and locations with less than 48 data points in a year were removed to ensure each monthly segment included at least four data points. For each location, the average flow and temperature and the total unused thermal energy were gathered for each month. If there were insufficient data points for a single month, data points were added from the adjacent month and then averaged over the new time period. With the refined data, R was used to code graphs for each location with time on the horizontal axis and either flow, temperature, or thermal energy on the vertical axis. Each location was represented using a different colored line and labeled in the legend. A line representing average temperature, flow, and thermal energy was added in bold to each respective graph to demonstrate monthly trends across all locations (Dr. Alessandra Schider).

2.4 Ethics Statement

This study is based off of data sourced from energy producers in Iceland and other digital forms of mapping data and therefore did not include any human subjects or direct contact with natural spaces for data collection purposes. It did, however, include analysis of data that detailed a source of waste from these energy producers which, taken in the wrong context, may have an unintended effect on consumer perception of these producers. This study is intended to understand possible positive uses of this source of thermal energy, and as such, the discussion of these data focuses on forward-thinking solutions to emphasize the potential of harnessing thermal energy from these hot water bleed sites rather than any negative implications that these data may suggest. All recommendations on locations for best thermal energy reuse projects made during this study are just that, and if future work decides to implement anything described in this paper it is imperative that a thorough analysis is conducted of the impacts that such a project may have on the people, the surrounding landscape, and the environment at large to ensure ethical implementation.

2.5 AI Statement

AI was not used in any part of this project, including but not limited to the research, data organization and analysis, and the writing portions of this project.

3. Results

3.1 National Data

The data from Orkustofnun B were used to visualize national energy data across Iceland. In terms of total heat use in Iceland in 2023, Veitur ohf, the energy producer that services the Reykjavík, dominates with 51% of total heat use. Comparing the heat use by sector shows that residential heat use accounts for roughly half Iceland's heat use (Fig 3).

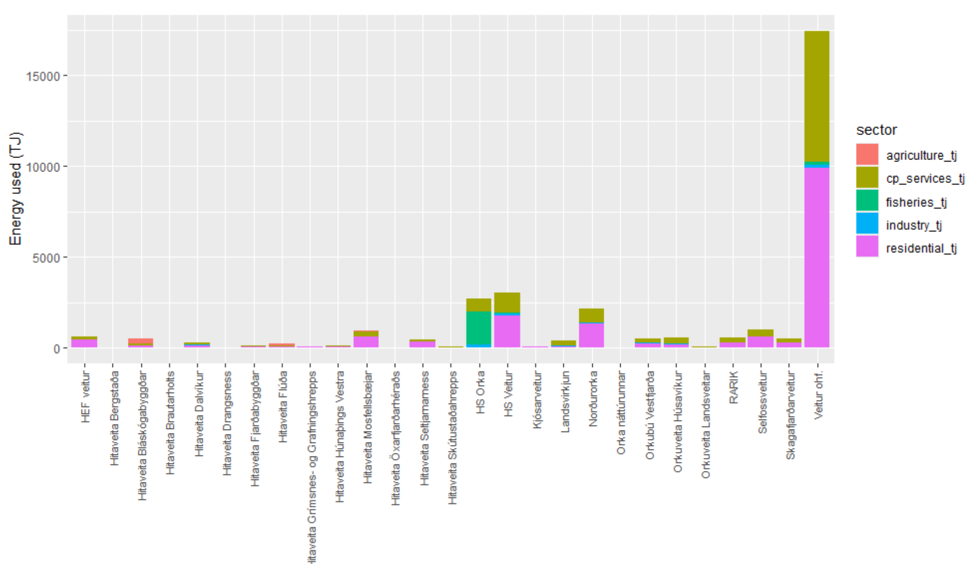

Figure 3. Heat energy use in 2024 in terajoules by Icelandic energy producers. The sector of use is displayed using different colors (Dr. Alessandra Schnider).

Removing Veitur ohf. from the plot allowed for a more detailed visual of the smaller energy producers. Norðurorka was the 4th largest MAP in 2023 and accounted for 6.4 % of Iceland's MAP heat us in 2023. Norðurorka's total heat use was divided into two main categories: 62% residential and 36% C&P services. The remaining 2% was split between agriculture, fisheries, and industry (Fig 4).

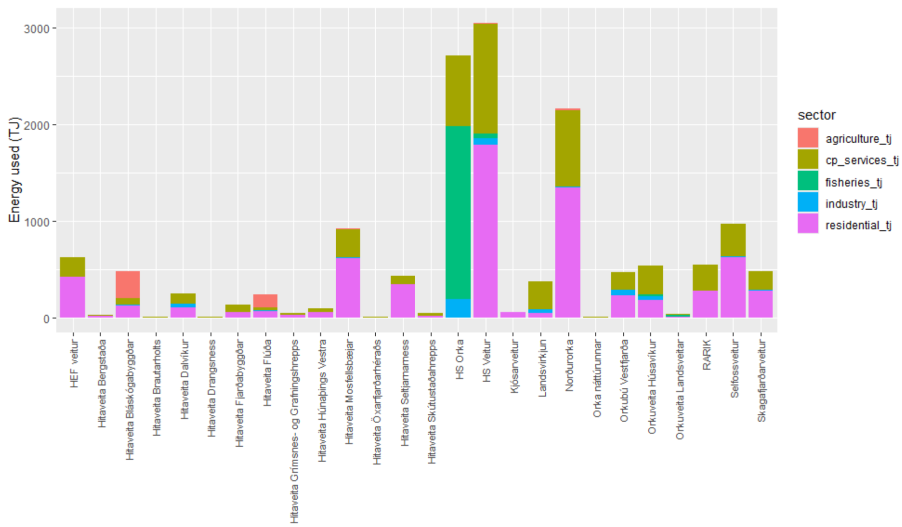

Figure 4. Energy use in 2024 in terajoules by Icelandic energy producers, divided by sector. The sector of use is displayed using different colors. Veitur ohf. is not pictured to allow for better comparison of the smaller scale producers (Dr. Alessandra Schnider).

3.2 Regional Data

A regional analysis of Skagafjördur and Eyjafjördur mapped the 137 geothermal readings by temperature, flow, and thermal energy (Fig 5, 6, 7, respectively). Eyjafjördur displayed a slightly higher average temperature value (54.97 °C) than Skagafjördur (52.97 °C). Across all locations, the average temperature was 54.06 °C. The hot water bleed site with the highest temperature of 98 °C was at Langhús, located in Fljótin in Skagafjördur (Fig 5).

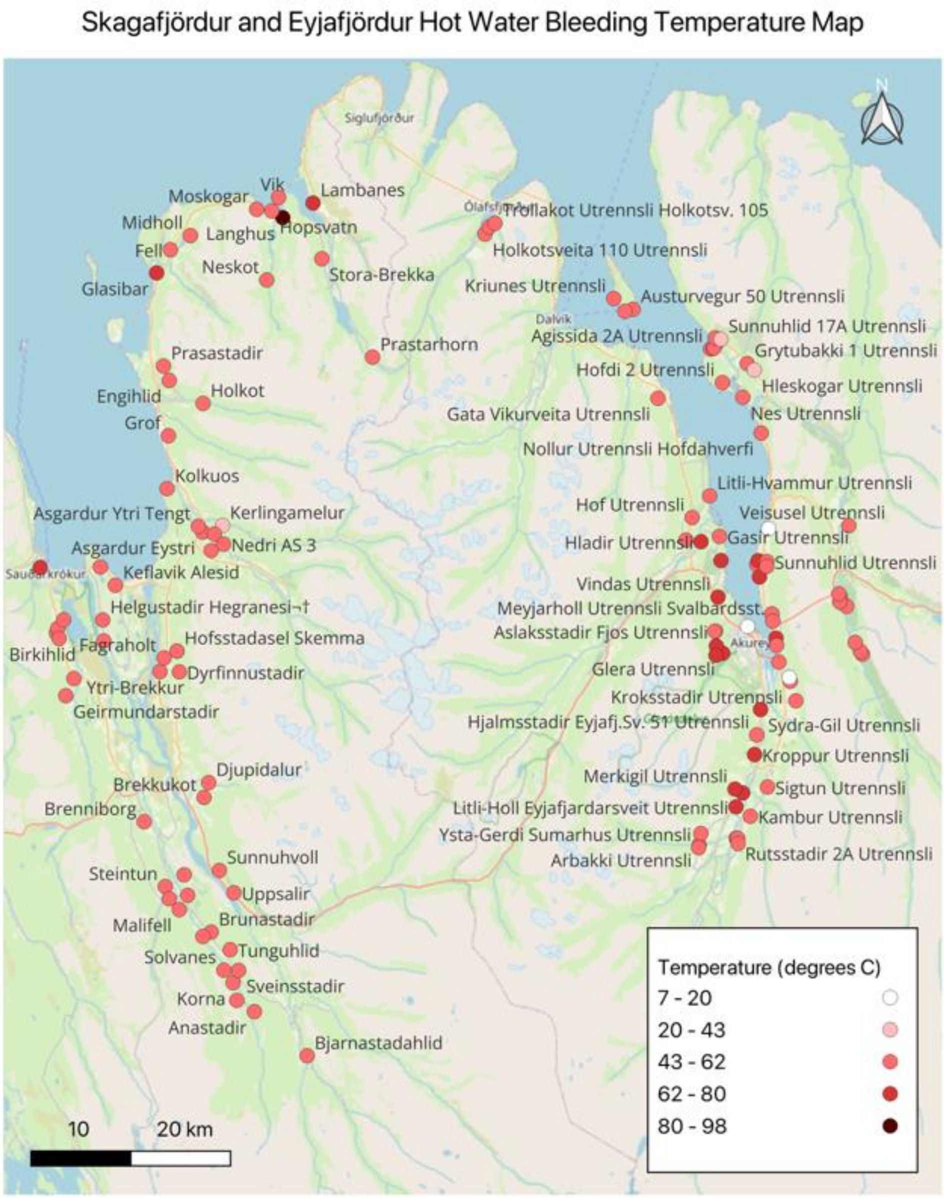

Figure 5. Map displaying the variability in temperature of hot water bleed locations within Skagafjördur and Eyjafjördur. Darker red indicates higher temperatures and paler red lower temperatures.

A flow comparison between the two regions shows a higher median flow rate in Skagafjördur (0.119 L/sec) than in Eyjafjördur (0.033). Some of the highest flow locations are in rural areas in Skagafjördur. The location with the highest flow was located at Helgustaðir in the municipality of Sauðárkrókur in Skagafjördur, with a value of 1.49 L/sec (Fig 6).

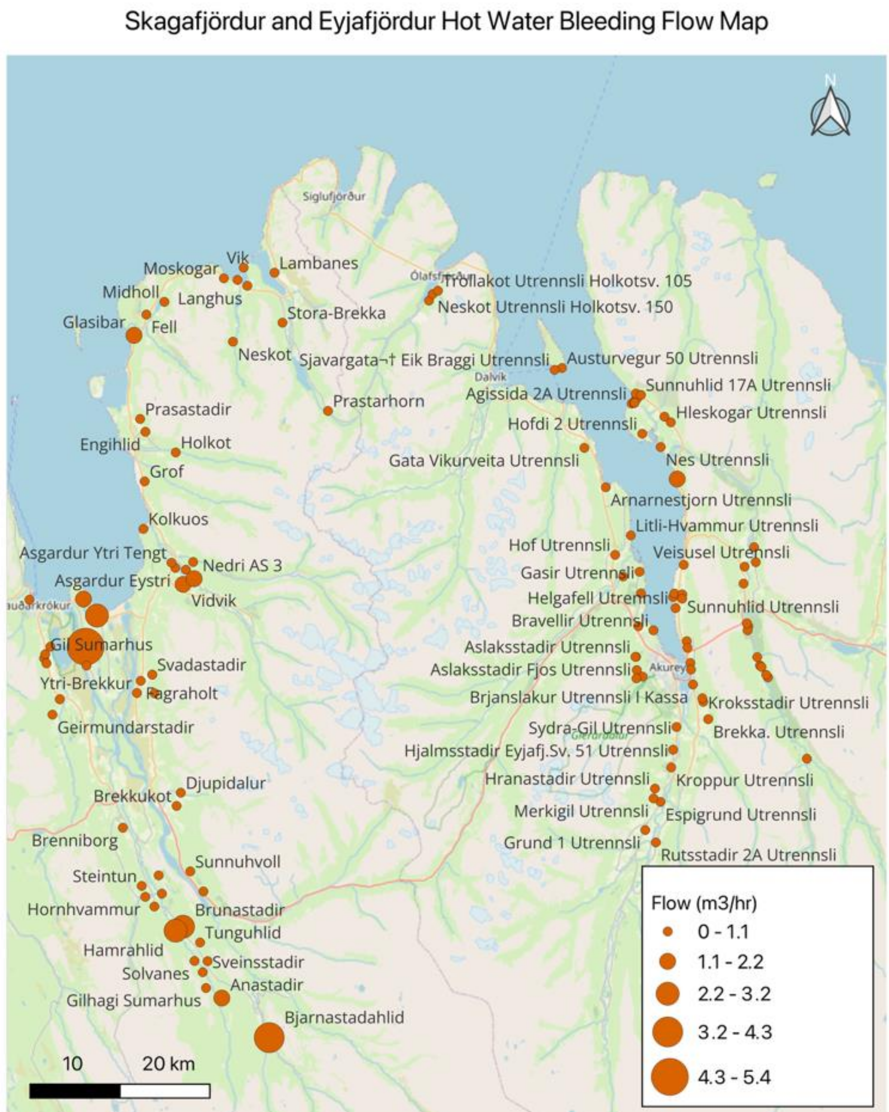

Figure 6. Map displaying the variability in flow of hot water bleed locations in Skagafjördur and Eyjafjördur. Larger points indicate higher flow, and smaller points indicate lower flow.

The thermal energy follows a similar trend as the flow map, with the highest thermal energy areas aligning with the highest flow areas, especially in rural Skagafjördur near the end of the fjord. The location with the highest thermal energy area was at Helgustaðir in at the end of the fjord in Skagafjördur with 2.082 GWh/yr (Fig 7).

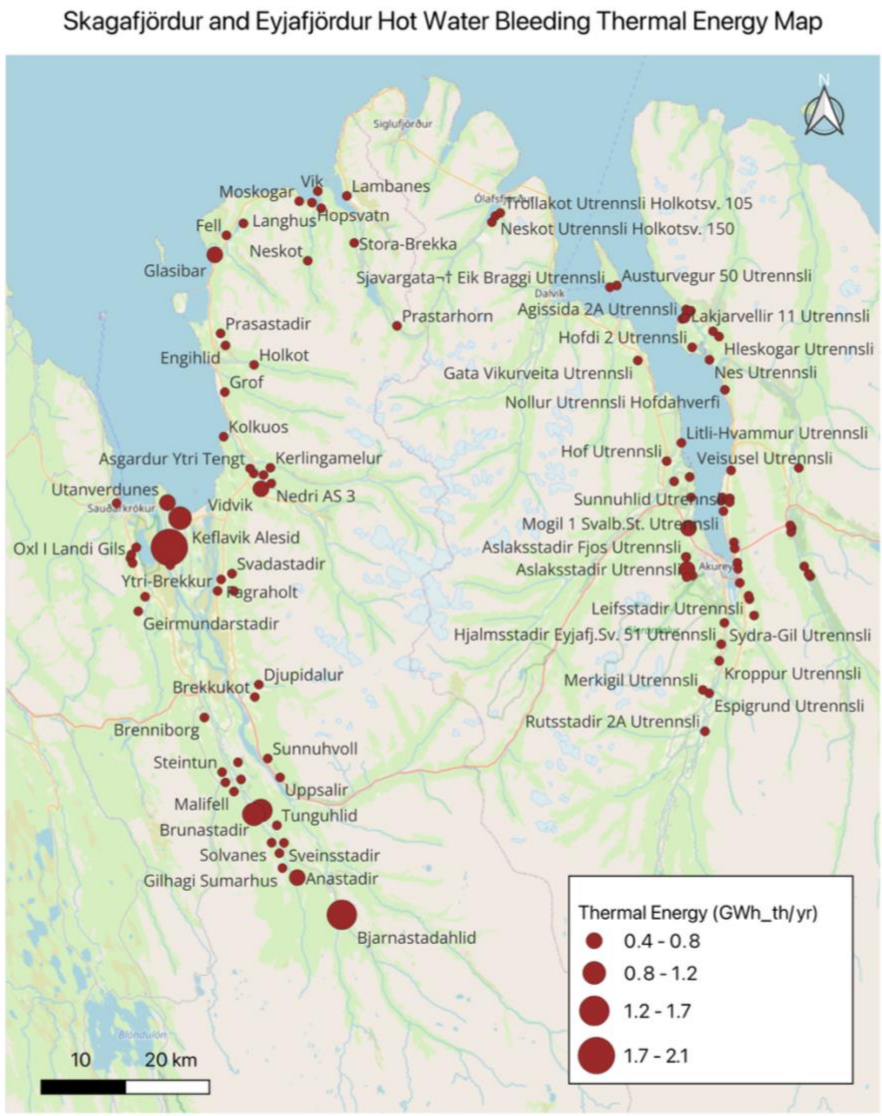

Figure 7. Map displaying the variability in thermal energy of hot water bleed locations in Skagafjördur and Eyjafjördur. Larger points indicate higher thermal energy, and smaller points indicate lower thermal energy.

The results of volume, flow, temperature, and thermal energy calculations within Eyjafjördur, Skagafjördur, and across both regions are shown in Table 3.

		Eyjafjördur	Skagafjördur	All Data
Volume (m^3)	*Mean*	1,376	5,443	3,068
	Total	110,106	310,268	420,374
Flow (L/sec)	*Median Flow*	0.033	0.119	0.061
	Total	4.10	11.78	15.88
Temperature (°C)	*Minimum*	7.00	41.26	7.00
	Maximum	71.69	98.00	98.00
	Median	51.45	56.80	53.18
Thermal Energy (GWh_{th}/yr)	*Median*	0.152	0.049	0.097
	Total	16.000	5.544	21.544

Table 3. Table displaying key statistics from the Skagafjördur and Norðurorka data including minimum, maximum, median, and totals of bleed volume, flow, temperature, and thermal energy.

The second section of regional results involves hot water bleed characteristics of the top five hot water bleed sites (Table 3). Flow, temperature, and thermal energy values are compiled for each location. Additionally, predicted values for square meters of a tomato greenhouse and cubic meters of aquaculture that the site could support are calculated (Dillman, 2018). Information gathered on the surrounding geography and location within the heat supply network is also included with each table.

The hot water bleed location with the highest thermal energy is Helgustaðir. Helgustaðir is located in Skagafjördur in the municipality of Sauðárkrókur. It is about 50m above sea level on a relatively flat grassy marsh between where the two branches of the river Héraðsvötn flow into the ocean. It is located at the very southern end of a branch of the heating supply pipe network that also provides heat to much of Sauðárkrókur.

The hot water bleed location with the second highest thermal energy is Bjarnastaðahlíð. Bjarnastaðahlíð is located in Skagafjördur in the municipality of Hverholaveita. It is well into the fjord, located at 210 meters above sea level right next to the river Húseyjarkvisl and surrounded immediately by flat farmland, but not far from the steep walls of the fjord. The heating supply pipe network it is located on runs along the inner section of the fjord, increasing in elevation by about 100m from north to south. Bjarnastaðahlíð is about 4km downstream of a pumping station.

The hot water bleed location with the third highest thermal energy is Hamrahlíð. Hamrahlíð is located in Skagafjördur in the municipality of Hverholaveita. It is well into the fjord, located at 90 meters above sea level in close proximity to the river Húseyjarkvisl and surrounded by flat farmland. Hamrahlíð is at the one side of a T branch at the very northern end of the same heat supply pipe network as Bjarnastaðahlíð.

The hot water bleed location with the fourth highest thermal energy is Brúnastaðir. Brúnastaðir is located in Skagafjördur in the municipality of Hverholaveita. It is well into the fjord, located at 120 meters above sea level surrounded by flat farmland. Brúnastaðir is at the other side of a T branch opposite Hamrahlíð at the very northern end of the same heat supply pipe network as Bjarnastaðahlíð and Hamrahlíð.

The hot water bleed location with the fifth highest thermal energy is Keflavík. Keflavík is located in Skagafjördur in the municipality of Hegranes-Hofsstaðaplass. It is on mostly flat farmland at 50m above sea level in close proximity to the ocean. It is at the very northern end of a heat supply branch that is a part of the same heat supply network as Helgustaðir that supplies most of Sauðárkrókur, about 6km downstream from a pumping station.

Municipality	***Sauðárkrókur***	***Hverholaveita***	***Hverholaveita***	***Hverholaveita***	***Hegranes-Hofsstaðaplass***
Location	**Helgustaðir**	**Bjarnastaðahlíð**	**Hamrahlíð**	**Brúnastaðir**	**Keflavík**
Thermal Energy (GWh_{th}/yr)	2.081	1.438	1.067	1.062	0.873
Median temperature (°C)	53	51	52	51	51
Flow (m^3/hr)	5.38	3.98	2.84	2.86	2.36
Estimated size of tomato greenhouse (m^2)	1015	701	520	518	426
Estimated size of Arctic Char aquaculture (m^3)	427	295	219	218	179

Table 3. Key data including flow, temperature, thermal energy, and estimations for the size of a tomato greenhouse and Arctic Char fish farm from the hot water bleed locations with the five highest thermal energy values in Skagafjördur and Eyjafjördur. All of these locations were located in Skagafjördur.

3.3 Temporal Data

The time-series plot of monthly average water temperature displays fairly consistent temperatures for most locations. The average water temperature at a location varies between 71°C and 20 °C. On average the water temperature is slightly lower in the summer months than in the winter months, although not significantly. For the majority of locations, the plot displays little visual variation in the temperature over the year, save a few outliers that display large variation over the year.

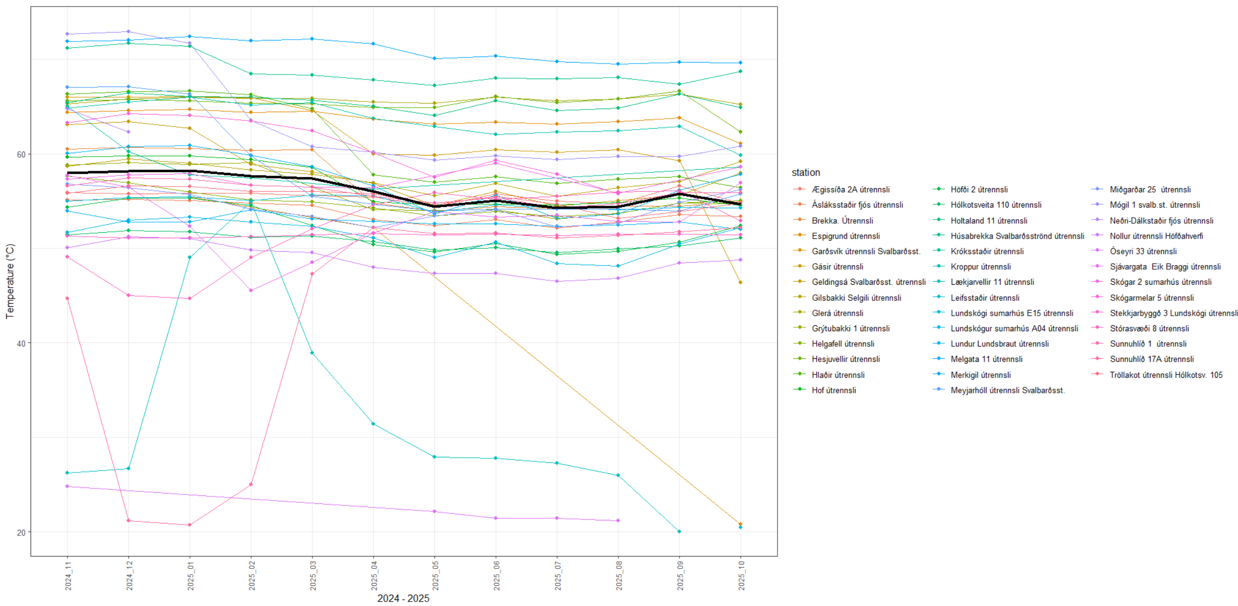

Figure 8. *Time-series plot of hot water bleed temperatures over the past year from Norðurorka. Each colored line represents a different location. The dark line represents the mean temperature across all locations (Dr. Alessandra Schnider).*

The monthly flow plot shown below in Fig. 9 displays a recurring trend across most of the locations. The flow reaches a peak in June, then dips in July, and then peaks once again in August. The average flow is slightly higher in the summer months and lower in the winter months.

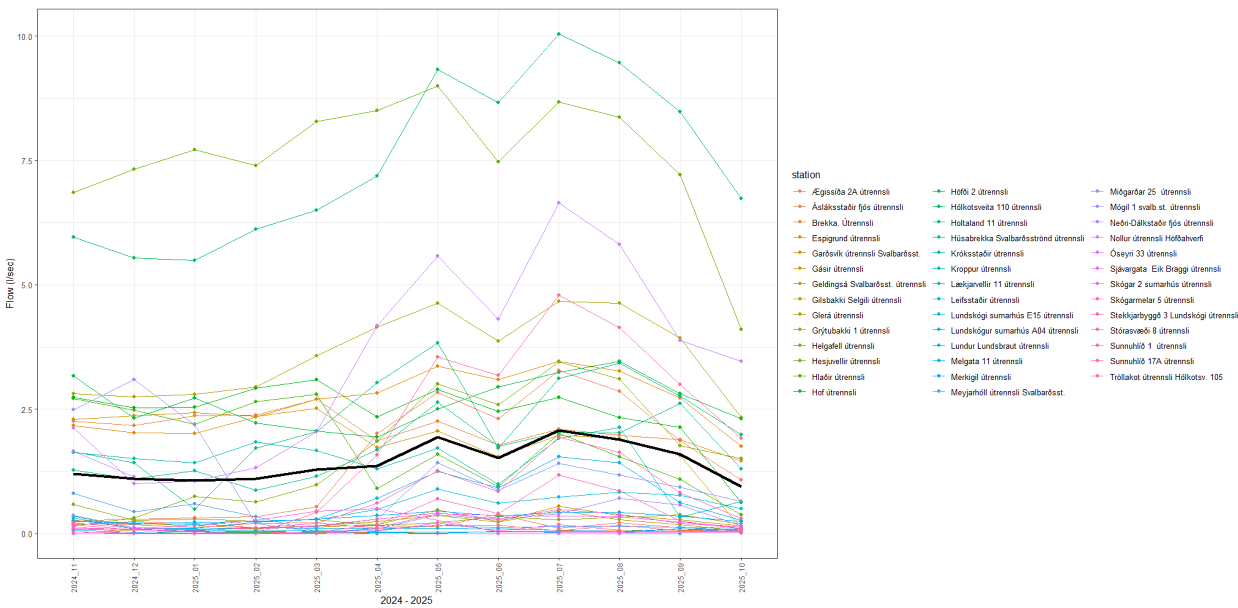

Figure 9. Time-series plot of hot water bleed flow over the past year from Norðurorka readings. Each colored line represents a different location. The dark line represents the flow temperature across all locations (Dr. Alessandra Schnider).

Seasonal thermal energy trends displayed in Fig. 10 are similar to seasonal flow trends in Fig 8. The average thermal energy during the summer months is slightly higher than the average thermal energy during the winter months.

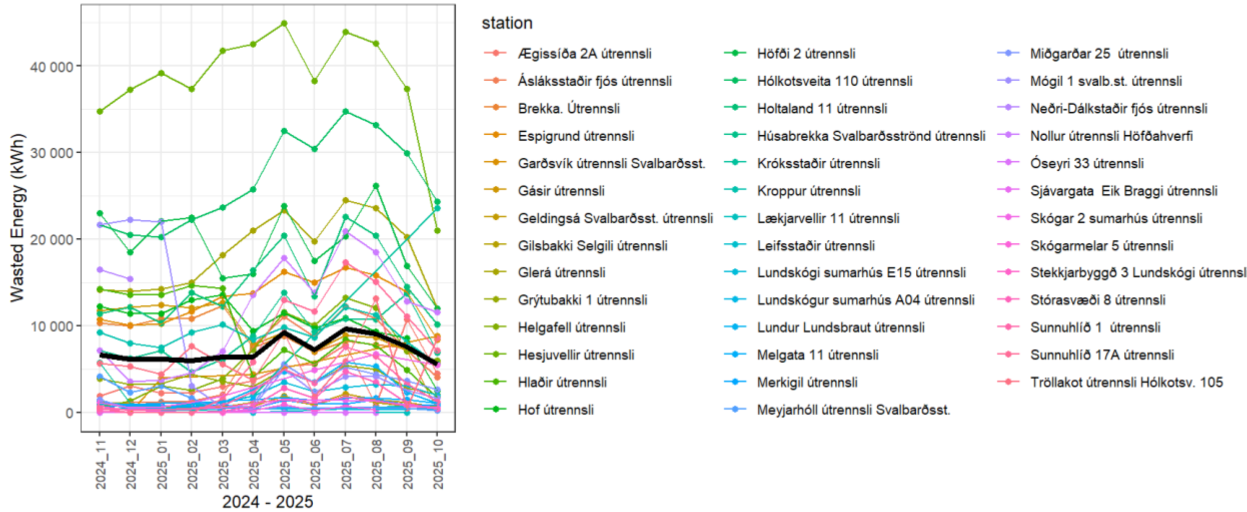

Figure 10. Time-series plot of hot water bleed thermal energy over the past year from Norðurorka readings. Each colored line represents a different location. The dark line represents the flow thermal energy across all locations (Dr. Alessandra Schnider).

4. Discussion

4.1 Feasibility and Scale of Reuse at Highest Thermal Energy Locations

The feasibility for reuse of geothermal hot water depends on the amount of thermal energy available and the water temperature at the bleed site. Other crucial factors include access to water, land availability, and existing infrastructure. After filtering out the best possible candidates to focus hot water bleed reused efforts on based on the locations with the highest thermal energy, we can then analyze the other factors to determine if it is a suitable location for greenhouses or aquaculture and if so, at what scale.

Helgustaðir has 2.081 GWh/yr of unused thermal energy. It is located between the two branches of the river Héraðsvötn, indicating consistent access to pure water. While the surrounding grassy marshes may not be optimal for greenhouse construction, its flat terrain may be suitable for an inland fish farm. The bleed water temperature (53 °C) is well above the range required for fish farming. There is enough thermal energy to provide for just under 430 cubic meters of an Arctic Char inland outdoor fish farm (Dillman, 2018). While this is not large enough for a commercial fish farm (Ragnarsson, 2015), it could act as a small pilot project as a proof of concept. Skagafjördur already has infrastructure related to fish farming – Ísponica in

Hófsos, which combines aquaculture and hydroponics and a fish tannery, and Sútarinn in Sauðárkrókur. There is likely knowledge on fish farming as well as the necessary facilities for management and export of this industry. Overall, with sufficient energy, adequate temperature, and suitable conditions, a small-scale fish farm is a viable option at Helgustaðir.

Bjarnastaðahlíð's has 1.438 GWh/yr of unused thermal energy. It is located next to the river Húseyjarkvisl, providing consistent access to pure water. Located on farmland, the location already has infrastructure that may make greenhouses feasible. The presence of these operations indicates access to land and infrastructure that could support a greenhouse. The Bjarnastaðahlíð bleed site has enough thermal energy to support about 700 square meters of a tomato greenhouse. (Dillman, 2018).

Hamrahlíð features characteristics like Bjarnastaðahlíð including proximity to the river Húseyjarkvisl and nearby farmland providing established farming infrastructure. With 1.067 GWh/yr of unused thermal energy, it could support slightly over 520 square meters of a tomato green house (Dillman, 2018).

The Brúnastaðir bleed site has 1.062 GWh/yr of unused thermal energy. It is located a kilometer away from Hamrahlíð with similar features, though it is further from the river. Because it is in proximity to Hamrahlíð there is the potential to combine hot water bleed thermal energy from both locations which would almost double the amount of available thermal energy. Brúnastaðir on its own has 1.067 GWh/yr of unused thermal energy which could power just over 515 square meters of a tomato greenhouse (Dillman, 2018). Using thermal energy from both Brúnastaðir and Hamrahlíð bleed sites, the two could support 1,038 square meters of tomato greenhouse. For context, the tomato cultivation greenhouse Friðheimar which now produces a significant amount of tomatoes for Icelandic consumption began as a 1,174 square meter greenhouse (Friðheimar, n.d.), only slightly larger than the greenhouse which could be supported at Brúnastaðir. Hot water bleed locations in proximity to others show potential for consolidating thermal energy for larger scale projects.

Keflavík's location on farmland means it has existing infrastructure for a greenhouse and adequate space for either a greenhouse or aquaculture. Its proximity to the ocean and the estuary of the Austari-Héraðsvötn indicates access to water, although the saline nature of it may not be the ideal source that is necessary for crop irrigation so aquaculture may be a better choice. With 0.873 GWh/yr of thermal energy available it would be able to support about 180 cubic meters of aquaculture (Dillman, 2018). An inland fish farm of this size may not be large enough for it to a feasible project, therefore smaller scale uses such as snow melt or using the thermal energy to increase the efficiency of heating systems that already exist may be the most realistic option.

4.2 Influences of Flow, Temperature, and Thermal Energy

It is clear that the water temperature, flow, and amount of usable thermal energy at a hot water bleed location depend on both site-specific factors as well as broader seasonal changes.

4.2.1 Site-specific factors

Close observation and analysis of the trends between location of the bleed site and its position within the heat supply pipe network revealed loose trends on their effect on thermal energy availability.

One notable trend is that the hot water bleed sites with the five highest amounts of unused thermal energy are all at the very end of their respective pipe network branch. Hot water bled from the very end of the pipes pulls water through the rest of the pipe network, aiding water flow to locations along the way. Additionally, since the heated water is distributed from a central location, branches that are further from the distribution point must travel longer distances. This likely makes higher flow bleeds necessary to maintain an adequate temperature and pressure. While the highest flows within a system aren't always located at the very end of the branch, the fact that this trend is seen for the top five locations strongly supports this causation and suggests that other unknown factors may be the reason for inconsistencies in this trend seen at other sites.

There was three times greater thermal energy from hot water bleeds in Skagafjördur than in Eyjafjördur. This suggests that hot water is bled more Skagafjördur, possibly because many of the bleed locations are more rural than those in Eyjafjördur. However, differences in the data collection for the sites may have also had an influence that could skew this result. Temperature and cumulative volume data for each site in Eyjafjördur were taken by an electronic metering system on average 3,762 times per location over the data collection period. In Skagafjördur, however, the cumulative volume data was taken once a year with only one temperature measurement. Without more data points it is likely the single data point is much less representative of the actual value and therefore difficult to confirm trends across datasets.

4.2.2 Seasonal Hot Water Bleed Trends

The influence of environment and demand also has an effect on the seasonal trends of thermal energy. When environmental temperatures are warmer, there is less demand for residential heating. However, it is still necessary to maintain an adequate temperature and water flow at the destination. As a result, when temperatures rise and residential heating water demand decreases, hot water bleed flow increases. These seasonal effects are important when considering the availability of thermal energy over the course of the year which influence the possibilities for reuse. It is advantageous to consider reuse projects that require high amounts of thermal energy when it is available in the warmer months, such as hay or crop drying. Considerations will have to be made to ensure adequate thermal energy availability throughout the year for reuse projects which require more heating in the colder months, such as greenhouse heating. To ensure a constant availability of thermal energy, one approach may be to base the system's capacity around the lowest energy availability (the winter months in this case). Alternatively, if excess thermal energy could be captured and stored during peak energy availability in the summer, the system could use this stored energy when there is less available in the colder parts of the year. This strategy would maximize thermal energy utilization from the hot water bleeds, also maximizing the size of greenhouses, aquaculture, or other uses that the thermal energy from these hot water bleeds could support.

4.3 National Hot Water Bleed Trends

National Icelandic data allow us to understand the state of energy and heat use in Iceland so we can determine energy producers or regions that would benefit most from using thermal energy from hot water bleeds. Once identified, these energy producers or regions may be beneficial to focus future hot water bleed analysis on.

The energy company Veitur ohf. services the Reykjavík area, a much more condensed residential area than is seen in the rest of Iceland. As the case study of Brúnastaðir and Hamrahlíð has shown, proximity of hot water bleeds creates a potential for combining the thermal energy available for reuse for larger scale projects. An area like Reykjavík which requires a lot of heating with a small area has the potential for consolidating bleed sites to increase the amount of thermal energy available. Because of the large amount of infrastructure, urban areas also have the benefit that recovered thermal energy from bleeds can be put towards increasing the efficiency of systems that are already in place instead of required enough energy and resourced to construct and power a new an entirely new piece of infrastructure. For example, a small amount of thermal energy could be put towards decreasing the amount of energy that pools need to use to heat their water. This allows much smaller amounts of heat to be put towards efficient use. One important note is that because of the more compact nature of the district heating system in Reykjavík, the heating system needs to transport water shorter distances so there is less need for hot water bleed than in the more rural areas of Skagafjördur and Eyjafjördur. So, even if smaller amounts of thermal bleed energy could be put to use to increase the efficiency of existing infrastructure, there may still not be enough thermal energy for it to be economic. The specifics of hot water bleeds in urban areas are a possibility for further research.

Understanding and predicting what thermal energy availability from hot water bleeds looks like across Iceland depends on the distribution of heat use between sectors as well as how it compares to the data we have had the opportunity to analyze. From a comparison of national heat use by sector it is shown that residential heat use accounts for almost half of Iceland’s total heat use. Because almost all of Iceland is heated using geothermal district heating systems and similar hot water bleedings likely occur in other areas, the large extent of residential heat use suggests that there may be locations with significant amounts of unused thermal energy outside of just the regions this study focused on. Additionally, the fact that Norðurorka only represents 6.4% of Iceland's heat use from MAPs and only 8% of Iceland's residential heat use is another indication that parts of Iceland outside the area of this study likely have significant unused thermal energy. Understanding the specifics of hot water bleeds and unused thermal energy availability in other regions of Iceland is left for future research.

We can compare the amount and sector of heat use between producers to predict which energy producers have similar thermal energy availability as Norðurorka and therefore have potential for similar scale thermal energy use projects. Energy producers with high overall heat use in addition to high ratios of residential heat use are optimal for introducing hot water bleed use initiatives because they are most likely to have similar amounts of thermal energy from bleeds as Norðurorka. HS Veitur, which has slightly higher total heat use of which a similar fraction is put towards residential heating is most likely to have similar amounts of unused thermal energy as was found from Norðurorka. Extrapolating the exact amounts, however, requires more research into factors including but not limited to the density of residential buildings, the distance from geothermal well fields, and annual environmental temperatures for each location serviced by the producer. HS Orka, although it has higher overall heat use than HS Veitur, puts a large fraction of heat use towards fisheries rather than residential. Because the heated water is likely distributed with a different system across various sectors, predictions for the scale of thermal energy availability for other sectors cannot be compared to what has been shown for residential heating. Further research will have to be done to understand the mechanics and scale of thermal energy loss in other sectors.

5. Conclusion

Compiling hot water bleed data and understanding the scale at which it is available is a necessary first step in determining the feasibility and optimal locations to put it to use. Using mapping tools can provide a visual to understand how water temperature and flow as well as how the location of a bleed site within a heat supply network has an influence on the thermal energy that is available. Comparing heat use data across producers places our findings in a national context and allows us to understand both the relative scale of the data we are looking at and postulate the potential that using this hot water bleed energy at a larger scale might have.

Results reveal the most optimal locations within Skagafjördur and Eyjafjördur to consider implementing hot water bleed reuse solutions. Calculations determine that there is sufficient thermal energy for reuse on the scale of heating moderately sized greenhouses and pilot aquaculture projects. The maps indicate where bleed sites are in close enough proximity for combined use to increase the amount of total thermal energy available. Higher thermal energy output in the summer and lower output during the winter indicate that seasonality is an important consideration when determining how much thermal energy can be put to use during a year.

Overall, the Skagafjördur and Eyjafjördur data we analyzed was a relatively small part on the national scale, indicating large potential for reusing this resource outside of the analysis we did.

These findings hold implications for energy producers which have access to these hot water bleed sites. As an effectively free source of thermal energy, there is great potential to harness it in order to increase the efficiency and maximize the benefits of their services. The feasibility assessment of tomato greenhouses and aquaculture at these bleed locations is a useful tool to visualize the scale of the thermal energy available, but if a site is chosen for a project to reuse this thermal energy, more extensive research on the location and feasibility is required to determine optimal use. This study begins the conversation on a largely unstudied and unrecognized source of unused thermal energy that has great potential for use. Further research may conduct more detailed feasibility assessments as well as expand the analysis of hot water bleed sites to other regions or service areas of other energy producers in Iceland.

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