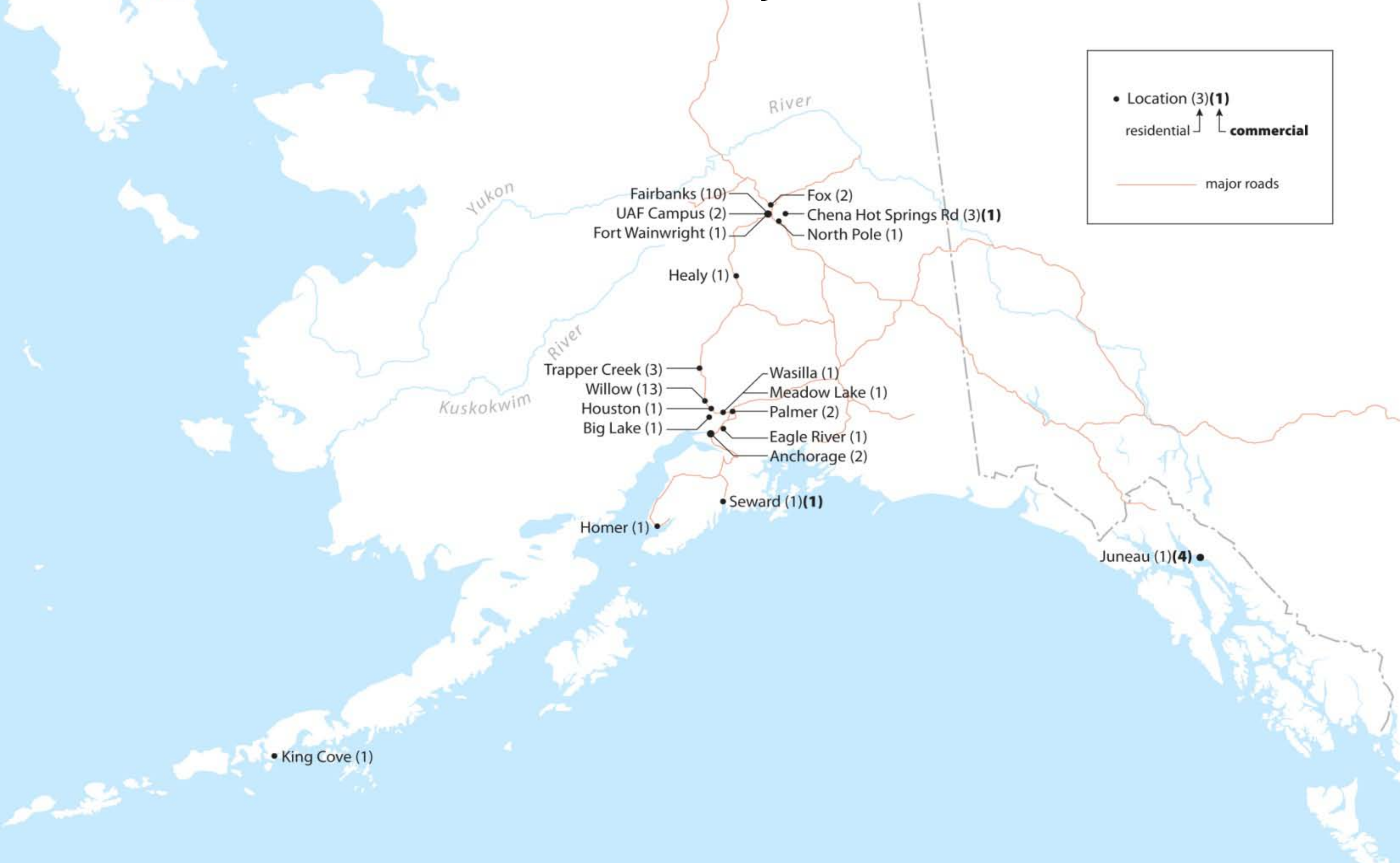
Ground-Source Heat Pumps in Cold Climates

The Current State of the Alaska Industry, a Review of the Literature, a Preliminary Economic Assessment, and Recommendations for Research



A report for the Denali Commission

Prepared by:
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The Current State of the Alaska Industry, a Review of the Literature, a Preliminary Economic Assessment, and Recommendations for Research

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Executive Summary

While ground-source heat pump (GSHP) technology for space heating and cooling is well established, with widespread implementation across the U.S., information and experience specific to the practicality of using it in cold climates is limited. In Alaska, the use of GSHPs for residential and commercial space heating is uncommon, though several high-profile GSHP installations have occurred, which indicates a broader interest among homeowners, businesses, and government entities to explore this alternative space-heating method.

Within the U.S., the South has the highest percentage of GSHP installations (35%), followed by the Midwest (34%), the Northeast (20%), and the West (11%) (Lund, Gawell, Boyd, & Jennejohn, 2010). Ground-source heat pumps in the U.S. are typically sized for the cooling load (Navigant Consulting, Inc., 2009). This sizing is in contrast to GSHPs in Alaska and other northern areas, where the capacity of a GSHP is determined by the heating load of the building. Furthermore, in cold climates, it is probable that a GSHP will be used only for heating, unlike more moderate climates, where the ground is used for both heat extraction (space heating) and rejection (space cooling). This difference presents two disadvantages for GSHP efficiency in cold climates: heat is being extracted from relatively cold ground and is not being balanced by heat rejection used for space cooling.

Despite the relative novelty in Alaska, GSHPs are widely used in other cold climate regions in the world, as evidenced by their popularity in Scandinavian countries. In Sweden, 30% of the houses have GSHP systems (IEA, 2007). GSHPs in Sweden are typically designed to cover 90% of the annual heat energy demand, with an electric heating system as the backup heat source (Karlsson & Fahlen, 2003). In Norway, 15,000 GSHP systems have been installed, including 250 medium- and large-capacity nonresidential systems (Stene, Midttomme, Skarphagen, & Borgnes, 2008) and Finland has an estimated 46,000 units installed (Lund, Freeston, & Boyd, Direct Utilization of Geothermal Energy 2010 Worldwide Review, 2010). Heat pumps are widely used in Canada (Phetteplace, 2007), and in Europe, the market is growing (Rybach & Sanner, 2000).

The authors of this report—the Alaska Center for Energy and Power (ACEP) and the Cold Climate Housing Research Center (CCHRC)—have investigated and summarized information pertaining to the viability of GSHPs in cold climates in order to clarify the state of GSHP utilization in Alaska and provide a comprehensive resource of current knowledge for those interested in GSHP installations in cold climate regions such as Alaska.

Heat Pump Basics

A heat pump is a device that forces the movement of heat from a low-temperature medium to a higher-temperature medium. A GSHP transfers energy to and from a ground or water source to provide heating or cooling. In heating mode, the energy produced by this technology is considered partially renewable because solar and geothermal energy is mediated through the ground or water source. Depending on the generation source of electricity, the energy can be fully renewable.

A GSHP system is typically composed of a ground loop (tubing that passes through a ground or water source, transferring energy to circulating fluid), a heat pump (a mechanical system that allows for the extraction of energy from the ground-loop fluid), and a heat distribution system (the system that distributes heat throughout a conditioned space).

Left: Ground loops for installation at Weller School. Right: Heat pump units at the Juneau Airport.

A heat pump does not convert fuel to heat, but rather uses electricity to lift the temperature of its source (the fluid temperature from the ground loop) to a higher temperature used for space heating. For GSHPs in a heating mode, the most commonly used measure of efficiency is the coefficient of performance (COP). The COP is the ratio of heat output to work supplied to the system in the form of electricity.

$$COP = \frac{Quantity\ of\ Heat\ Delivered}{Energy\ Required\ by\ the\ Heat\ Pump}$$

For example, for electric resistance heating, the COP is 1.0, meaning that all of the electric energy is converted into heat. The energy required by a GSHP is also electrical, and includes the energy needed to run the compressor in the heat pump. Heat pumps have COPs higher than 1 because the energy delivered from a ground source is greater than the energy required to run the heat pump. A typical COP for a heat pump system is in the range of 2 to 4. This corresponds to an "efficiency" of 200-400%.

Cold Climate Considerations

One concern for locations with colder ground temperatures is that the low temperatures can lead to heat pumps operating at the bottom end of their designed operation ranges. An undersized ground loop could result in entering fluid temperatures that are too cold for the heat pump to operate efficiently and the heat pump will be unable to achieve the manufacturer COP.

Another consideration in cold climates is the potential creation of permafrost or seasonal frost due to thermal degradation caused by excessive heat extraction from the soil. There are concerns that the use of GSHPs in cold climates could lead to the creation of permafrost or seasonal ground freezing, which could cause heaving of utilities and structures near the ground loop, a reduction of COP over time, and other complications. Reports and journal articles address seasonal imbalances of heat extracted versus heat returned to the ground, and the possibility of soil freezing during the heating season. However, documented evidence of permanent soil degradation is scarce, and few long-term studies have been done to determine the effect of ground loops on the soil thermal regime.

The Alaska Industry

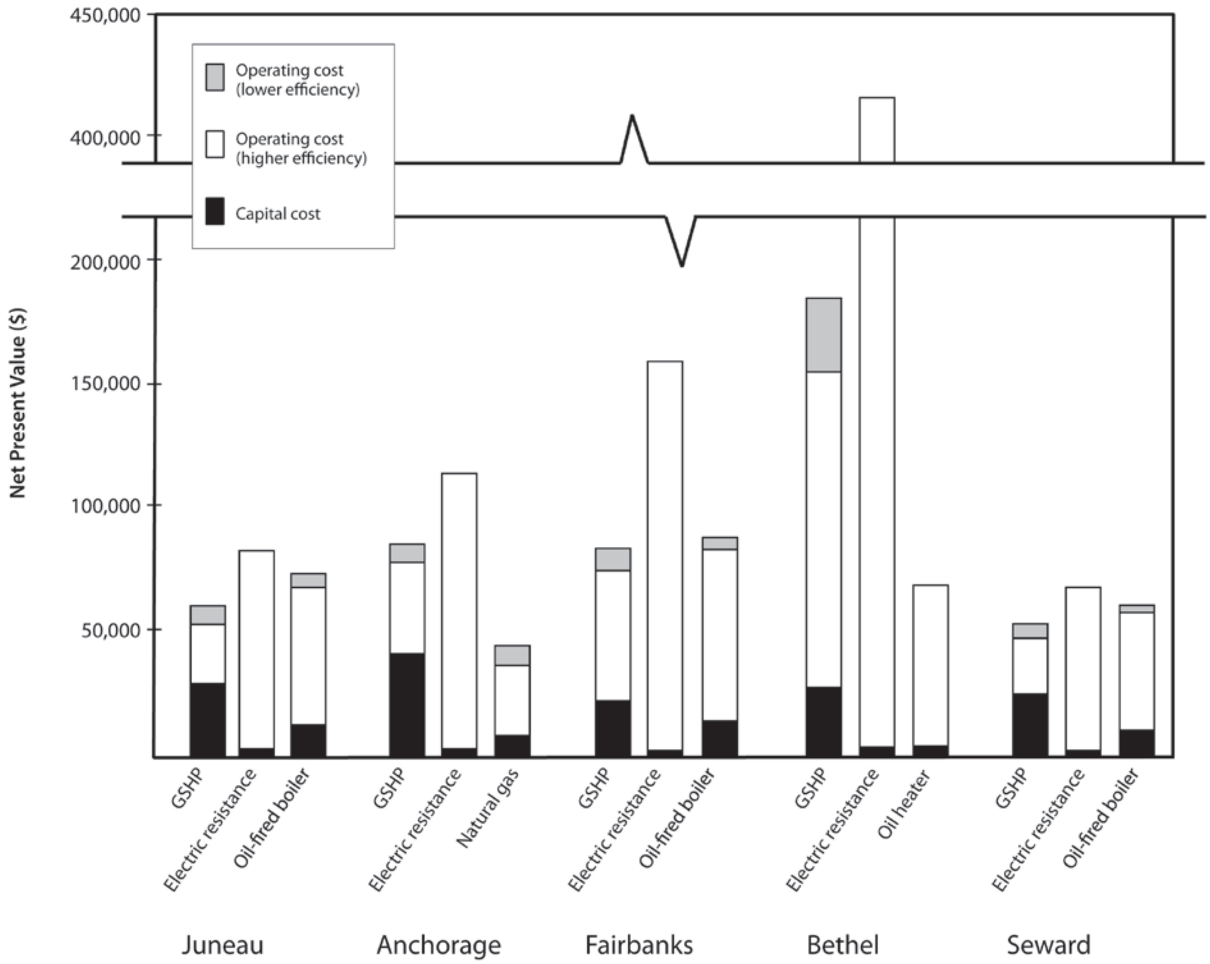
Alaska's GSHP industry is small, but recently has shown growth, with some prominent commercial installations in Juneau and several residential installations in Fairbanks. One large-profile commercial GSHP system has recently been installed at the Juneau Airport Terminal. In addition to the project's primary motivation, to reduce operating costs at the terminal, planners hope to increase public awareness of energy conservation and alternative energy (Fritz, 2008). This installation and other recent commercial installations are summarized in the report to provide examples of larger GSHP applications in Alaska.

Drilling to establish the vertical ground loops at the Juneau Dimond Park Aquatic Center

Residential GSHP owners interviewed for this report had installed a GSHP for a variety of reasons, but each homeowner reported that long-term cost savings was a strong motivation. Some homeowners found their systems to be low-maintenance, and more than one homeowner installed a GSHP in part because it is a partially renewable-energy technology. All of the residential GSHP owners interviewed reported satisfaction with their systems.

Preliminary Economic Assessment

Economic analyses were performed to compare the capital and energy costs of GSHPs with typical home-heating systems in five population centers in Alaska. The population centers examined include Juneau, Anchorage, Fairbanks, Bethel, and Seward. The net present value (NPV) of each system was calculated for each population center using the capital cost, annual energy, and maintenance costs over a 15-year period.



Results of the Economic Assessment

The capital cost of GSHP systems was higher than all other home-heating systems assessed for each population center. However, with the savings on annual heating energy costs, GSHP systems are the lowest-cost heating systems in Seward, Fairbanks, and Juneau. Homes in Seward, Fairbanks, and Juneau are primarily heated with heating oil. Ground-source heat pump systems use electricity to compress heat pulled from the ground and are fuel-efficient. For example, a GSHP system with a COP of 2.5 provides 2.5 kWh (kilowatt-hours) of heat for each kWh of electricity used by the pump. It is because of this fuel efficiency that homes using a GSHP for home heating can save on annual home-heating costs over fuel oil.

The GSHP system was unable to beat natural gas home heating in Anchorage because of the relatively low capital and energy costs of a natural gas home-heating system. The use of a GSHP system was also unable to beat a direct-vent laser stove, such as a Toyostove®, for home heating in Bethel. While the cost of heating oil is high in Bethel, the capital cost of a direct-vent laser stove is very low. Additionally, electricity in Bethel is expensive ($0.54 after the first 500 kWh each month).

Major Findings

A number of studies indicate that ground-source heat pumps (GSHPs) have been successful in cold climates. Based on this prior work, the range of COPs expected for professionally installed systems in Alaska is approximately 2.0 to 3.5 across a broad suite of locations, installers, heat sources, and heat pump manufacturers.

A number of studies discussed in the report addressed the issue of thermal imbalances that can be created in the soil because of a GSHP. While the long-term effects of GSHPs in soil with subfreezing temperatures is unknown (Bath, 2003), the concern of thermal degradation is site-specific. Whether ground temperatures can recover in the summer will depend on the region's climate, soil conditions at the site of the ground loop, and the sizing of the ground loop. In locations with low ground temperatures and a high annual heating demand, thermal imbalances are large concern.

Studies have identified barriers to growth of the GSHP market in the U.S. Barriers include high capital cost and lack of consumer knowledge and confidence in the technology (Hughes, 2008). Similarly, market diffusion is limited in Canada by factors such as high capital costs, nonstandardized systems, and actual performance that is less than promised (Hanova, Dowlatabadi, & Mueller, Ground Source Heat Pump Systems in Canada: Economics and GHG Reduction Potential, 2007). The GSHP market in Alaska faces these same problems.

In any part of the world, adequate design is necessary for GSHPs to meet performance expectations and have fewer maintenance issues. However, it is especially important in cold climates for the design of GSHP systems to match the parameters of the location. Poorly designed systems can result in a number of problems, such as decreasing COPs if the ground loop is undersized, because the soil cannot thermally recover (Cottrell, 2009). If the GSHP system is oversized, the capital costs will be higher than necessary, and excessive on-off cycling can stress the heat pump unit and reduce its operational efficiency. A common error in colder climates is to make the ground loop small and the heat pump large, which results in increased electrical use and decreased efficiency (Dr. John Straube, personal communication, November 11, 2010).

A lack of data on long-term GSHP applications in cold climates makes the decision to install one difficult. The longest study on using a GSHP in Alaska focuses on the ability of a GSHP to cool soil and maintain permafrost—not to heat a building (McFadden, 2000). Other studies note that longer monitoring projects are needed to determine under what circumstances a GSHP will cause thermal degradation and whether the COP can be maintained for several years (Mueller & Zarling, 1996; Nielson & Zarling, 1983).

Recommendations

The economic analysis of this report was conducted under the assumption of new construction, as opposed to retrofit, given the complexity of project-specific considerations and the need for accurate comparison. While this assumption served well for establishing preliminary economic considerations, investigating the economics of retrofitting a building with a GSHP system is critical for further understanding the feasibility of GSHPs in Alaska. Furthermore, the capital costs identified in the economic analysis were given as estimates by various installers from around Alaska. Due to the limited deployment of GSHP systems, some installers have little experience specific to GSHPs, which may be reflected in the given capital costs. It is recommended that these costs be carefully monitored, especially as more systems are installed and the experience of the industry grows, so that future analyses may offer refined numbers for economic comparison.

In 2008, the State of Alaska set a renewable energy generation target of 50% by 2025, and has since completed a guidance document to frame Alaska's energy future (AEA, 2009). Ground-source heat pump systems have several specific characteristics that make them an intriguing technology for consideration in meeting these targets; for example, they have efficiencies over 100%[1] and the ability to displace fossil fuel used for space heating, and they are either partially or fully renewable (depending on the generation source for electricity). It is recommended, therefore, that the state further investigate the role that GSHPs have in meeting renewable energy-generation targets, particularly with regard to public policy.

One finding from this report indicates that, in Alaska, GSHP systems are more viable where electricity costs are relatively low and heating costs are relatively high. Juneau, included in the economic analysis, displayed this relationship. These results can be roughly extrapolated to many other communities in Southeast Alaska that utilize hydropower. Not addressed are the potential ramifications of increased deployment of GSHP systems in these communities. Issues such as grid stability and capacity, supplemental or increased infrastructure costs, and relevant utility policy are examples of potential factors that need careful consideration to accurately assess the viability of GSHPs in a given community in Southeast Alaska. It is recommended, therefore, that potential GSHP-deployment stakeholders in relevant communities in Southeast Alaska carefully investigate integration ramifications of GSHPs if deployment of this technology is expected to grow.

While not considered in this report, air-source heat pumps (ASHPs) are attractive for moderate climates because they do not require ground coupling, substantially reducing capital costs and infrastructure complexities when compared with GSHPs. Recent technological advances may challenge the assumption that ASHP systems are not appropriate for cold climates (Roth, Dieckmann, & Brodrick, 2009), especially for locations like Southeast Alaska that have relatively mild temperatures for building heating load. Because several communities in Alaska that have a relatively mild climate also have relatively cheap electricity and expensive heating oil, a targeted analysis of ASHPs specific to these locations could help to determine whether ASHP systems represent a viable heating option.

There is insufficient clarity on the expected COP of cold climate GSHPs due to a lack of independently monitored GSHPs over periods greater than one to two years. A long-term monitoring period would last six to ten years. Further complicating the understanding of cold climate GSHP efficiency is a lack of standardization of the COP as an efficiency metric. Monitored GSHP systems should include documentation of the system configuration, measurement of COP, ground temperatures, climate data, temperature of the conditioned space, and electrical demand for heat pump components other than the compressor unit. Related to the recommendation for long-term monitoring of GSHP systems, research should address whether hybridization is necessary for cold climate applications of GSHPs. The installation of GSHP systems already suffers from high cost, which is increased with the inclusion of ancillary systems. Performance data should be collected on hybrid systems and compared to data on non-hybrid systems in similar locations.

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[1] Please see the discussion of coefficient of performance (COP) in the Heat Pump Technology Primer section of this report.