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Heat pump technology: An Alaska case study

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Heat pumps are a proven technology around the world and are being increasingly used in Alaska. Technological advances have improved their performance at low temperatures, making them more suitable for arctic environments. This analysis identified data related to 17 heat pumps installed in Alaska, which included air source, ground source, and sea water source systems. The data show that the average installed cost/kW of the heat pumps studied was $5,579. The minimum cost was just over $700/kW for a small air source minisplit system and over $12 000 for a complex vertical loop ground source heat pump. Air source heat pumps in Alaska have operated successfully down to −15 °C. Technological advances are ongoing that should enable further heat pump operation in colder climates. *Published by AIP Publishing*. https://doi.org/10.1063/1.4986584

INTRODUCTION

Heat pumps are space-conditioning appliances that can provide both heating and cooling of indoor areas by moving heat using a refrigeration cycle. Heat pumps take advantage of low-grade heat that is challenging to harvest with other technologies. This low-grade heat can include seawater, ground sources (even permafrost), relatively low air temperatures, and waste heat. The technology takes advantage of the phase change properties of a refrigerant to transport heat between spaces. When used for cooling, heat pumps extract heat from the indoors and pump it outside. In the heating mode, heat pumps extract heat from the outdoors and pump it inside. Heat pumps use electricity to power fans, pumps, and compressors, which run the refrigeration cycle to transfer heat. The ratio of the amount of heat transported to the amount of electrical energy used to power the process is known as the coefficient of performance (COP), which in the right conditions can be well over 3, indicating that for every 1 unit of electrical energy input, 3 units of heat energy are transported. Put another way, the process is 300% efficient where electrical resistance heating is 100% efficient.

Price volatility associated with hydrocarbons as well as a desire by many to transition towards lower-carbon forms of energy has resulted in renewed interest in this technology. According to Lund and Boyd (2016), the installed heating capacity of ground source heat pumps worldwide is over 50 GW and the annual heating production is over 90 TW h/year.

The performance of heat pumps in cold climates continues to improve. In recent years, several studies have been conducted to learn more about the options for heat pump use in Alaska. In the study by Stevens *et al.* (2015), heat pumps performed well down to about −15 °C. Other studies have examined the use of ground source heat pumps in Canadian cities and found sufficient economic payback to justify their expense in situations where the ratio of high heating oil costs and low electricity costs is favorable (Le Dû *et al.*, 2015). In the United States, ground source heat pumps have been used in all fifty states, with most applications concentrated in areas with cold climates and high population densities (Liu *et al.*, 2017).

There are limits to the use of heat pumps, and the economics depend on the price of electricity and competing fuel. In general, when air temperatures approach −17 °C, air-source heat pumps are nearing the limits of their operating parameters. In addition to the Alaska resources cited throughout this report, Efficiency Maine has created a simple online calculator that helps customers to compare heat pumps with other heating sources (Compare Home Heating Costs, 2017).

The emergence of natural refrigerants could further improve the environmental footprint and cold weather performance of heat pumps. Heat Pumps that use CO_2 as a refrigerant are becoming more common. CO_2 has significantly less global warming potential than synthetic refrigerants and has improved characteristics as a refrigerant for its ability to produce high output temperatures from relatively cool source temperatures (Stevens *et al.*, 2015).

Several hundred heat pumps are operating in the State of Alaska in both residential and commercial settings (Stevens *et al.*, 2013 and Meyer *et al.*, 2011). For residents already using electric heat, as in many areas of Southeast Alaska where inexpensive hydropower has made the use of electricity economical, heat pumps can be a good option. In addition, air-source heat pumps work well in the mild maritime climate of Southeast Alaska (Stevens *et al.*, 2015). In Juneau and Seward, sea life research facilities that have existing seawater intake infrastructure have been able to convert from fuel oil-fired boilers to seawater source heat pumps. These systems harvest heat from seawater where temperatures hover between 1 °C and 10 °C (Alaska Center for Energy and Power, 2014). For super-efficient structures that require minimal space heating, heat pumps can be good alternatives to fuel oil boilers, eliminating the need to buy heating oil and store it on-site. In addition, improved air-source ductless heat pumps are relatively inexpensive and easy to install and can function at cold temperatures (Stevens *et al.*, 2015).

This review of heat pump technology in Alaska is a result of Alaska Senate Bill (SB) 138. In this bill, the Alaska State Legislature created an uncodified section of law entitled: "Plan and Recommendations to the Legislature on Infrastructure Needed to Deliver Affordable Energy of the State to Areas That Do Not Have Direct Access to a [proposed] North Slope Natural Gas Pipeline." To support the Alaska Energy Authority (AEA) in its development of an Alaska Affordable Energy Strategy, the Alaska Center for Energy and Power (ACEP) contracted with AEA to document technology development needs specific to Alaska with regard to renewable and sustainable energy technologies. The intention was to determine what targeted, energy technology development solutions could be implemented in Alaska to make energy more affordable in the Alaska Affordable Energy Study area. While the focus was on technology research solutions, other factors such as logistics, labor, and training were also addressed. Drafts of technology reviews were vetted by expert roundtables in late February and early March 2016. These reviews are not meant to be exhaustive discussions of energy technologies in Alaska or proper designs for each technology, and they should not be used as guides for the choice and installation of specific systems.

METHODS

Data sources

Data from 17 heat pump projects were used in this study to estimate their effectiveness in the Alaskan environment and the approximate installed cost per kilowatt. These included 4 effluent/sea water source heat pumps, 7 vertical loop ground source heat pumps, 4 air source heat pumps, and 2 horizontal ground loop heat pumps. While this is a small percentage of the total number of heat pumps installed around the state, the heat pumps discussed in this report were chosen because their performance and cost data were available. Cost data came from engineering studies, State of Alaska grant applications, installation and maintenance records, and interviews with installers, owners, and facility staff members.

The majority of heat pumps described are large systems installed in sizeable public buildings. However, some smaller systems are also described. In rural areas of the state, the existence of small government and tribal offices often blurs the lines between residential and commercial installations and systems designed for residential dwellings are often utilized. In Wrangell, for example, small residential air-to-air mini-split heat pumps are used in utility and city offices.

Heat pumps generally produce lower temperature heat (55 °C) than conventional fuel oil boilers (82 °C). While technology is changing, lower temperatures may require differently designed heating, ventilation, and air conditioning (HVAC) systems to use the low-temperature heat produced by heat pumps efficiently (Alaska Sea Life Center, 2013). Conversions from fuel oil boilers to heat pumps can require significant indoor HVAC modifications. In other cases, building envelope modifications can allow the integration of a heat pump into the existing hydronic system. An example is the integration of new ground-source heat pumps in the existing 1580 square meter Senior House in Seldovia in 2013, which was able to integrate the heat pumps with the existing hydronic heating infrastructure because the insulation value of the roof, walls, windows, and doors was first upgraded in a weatherization effort. The improved envelope performance allowed lower temperature (55 °C–60 °C) heat pumps to meet 90% of the annual building heat load when one oil boiler was retained as backup for the coldest days (Baker, personal communication, 2016).

For heat pump retrofits, HVAC modifications are part of the necessary cost. Initially, we intended to separate costs for indoor HVAC work from the heat pump work performed outdoors and in the mechanical room. However, it quickly became clear that this would be overly difficult and subjective. As such, cost information for many of the systems in this analysis often includes HVAC modifications. Readers should keep this in mind when observing the high costs of some systems. These high costs often occur because of necessary modifications to the HVAC system in the existing building. These high installed costs per kW are especially evident on the large commercial systems discussed below.

As an additional caveat about costs, figures are approximate, and many come from feasibility reports. Discussions with installers in Interior Alaska indicate that installed system costs are typically lower than some costs reported here (Roe, personal communication, 2016).

No discounting of installation or operations and maintenance costs occurs in this analysis. All heat pumps discussed have been installed since 2010. The systems described range in size considerably. Some systems can be purchased from online retail websites and shipped to the consumer; others are large custom units.

DISCUSSION

Installed costs

The data in Fig. 1 show that ground-source systems have the widest range for installed cost per kilowatt thermal (kW_{th}), ranging from less than \$2000/kW_{th} to over \$12 000/kW_{th}. The same range is found for air-source heat pumps. In general, air-source mini-split style heat pumps are better suited for smaller projects due to their simplicity, cost, and ease of installation. The smallest range of installed costs/kW_{th} was found for seawater-source heat pumps. These systems are typically installed where a reliable intake of seawater is already in place, which helps to reduce costs. In this study, all systems over 200 kW_{th} are either seawater heat

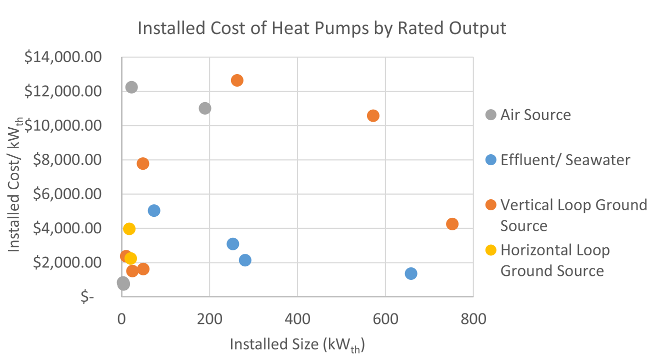

FIG. 1. The installed cost per kW_{th} (thermal) of rated output is compared with the rated output of 17 heat pumps of varying sizes and designs around Alaska.

pumps or ground-source heat pumps. The weighted average cost/kW_{th} of all 17 heat pumps studied is $5579. The weighted average cost is calculated by combining the total installed cost of all heat pumps by the total combined installed size in KW_{th} of all the heat pumps. The minimum cost for a heat pump analyzed in this study was just over $700/kW for a small air source minisplit system and over $12 000 for a complex vertical loop ground source heat pump.

The cost breakdown of components is addressed in a later section. Table I shows the weighted average cost/kW_{th} of the different types of heat pumps studied. Note that the study size was rather small, and some categories only have a couple of data points. This small sample size is demonstrated by the high cost of air-source heat pumps, where the high cost of larger systems masks the relatively low cost of smaller systems.

Installed costs by component

Because a broad range of heat pump installations has been described, generalizing the cost of components from one system to another is challenging. The costs of major components for some example projects are as follows:

Juneau airport ground-source heat pump

Installation of the heat pump was part of a renovation and expansion of the airport terminal. The old HVAC system was removed, and everything was replaced. The major heat pump component costs:

- Ground loops – 108 vertical wells @ 305 feet deep: ~$1 million
- Water-source heat pumps – 28: ~$460 000

Total Project Cost: $6 million (Building controls, ventilation, commissioning, mechanical room replacement, etc. are all additional significant expenses not broken out in this paper)

Cold climate housing research center (CCHRC) ground-source heat pump

This system replaced an oil-fired condensing boiler in an existing building, and no interior renovations were necessary. Costs include outdoor components and those in the mechanical room:

- Ground loop design: $1026
- Ground loop parts and installation: $26 491
- Heat pump parts and installation: $19 686

Total Project Cost: $47 203

Alaska Sea Life Center seawater-source heat pump

This system was a retrofit and required modification to the building mechanical room and HVAC system:

- Two 90-ton water-to-water heat pumps: $190 000
- Corrosion-resistant heat exchangers: $36 000
- Design: $100 000
- Labor: $150 000

TABLE I. Weighted average costs of different heat pump types.

Heat pump type	Weighted average of installed cost/kW_{th}
Effluent/seawater	$2096
Vertical ground loop	$7613
Horizontal ground loop	$3036
Air source	$10 359

Total Project Cost: $476 000 (The seawater intake was already installed, which otherwise would represent a significant expense.)

Other considerations

For vertical ground-source heat pumps, drilling is required. Drilling costs vary significantly around the state. Andy Roe of Alaska Geothermal indicated that his company entered the drilling business several years ago because of the high cost of drilling for their systems. In many areas of the state, a drill rig would need to be shipped in for projects, elevating costs.

Maintenance and repair costs

Figure 2 shows the annual cost of maintenance and repairs associated with different heat pumps around Alaska. These costs include the approximate cost of system replacement in 20–25 years. The figures do not include the electricity needed to run these systems (this is addressed in later sections). In most cases, these data were compiled from actual system cost and feasibility assessments developed as part of system planning.

Since the systems discussed in this analysis are relatively new, detailed long-term operation and maintenance (O&M) cost information does not exist. Andy Roe reports that maintenance on systems is minimal. All systems from Alaska Geothermal are sold with a 5-year warranty. Owners can expect a compressor replacement after approximately 12 years, which costs approximately $1000 and requires 5 h of labor. Tom Marsik and Clay Hammer, in Dillingham and Wrangell, respectively, report that the only maintenance their small mini-split air-source heat pumps require is vacuuming the filter. Tom reports that he spends about 20 min per year on maintenance. In these circumstances, it was assumed a cost of $50 per year and a 15-year replacement life.

The Alaska Sea Life Center is one of the few systems that have actual O&M cost information available. Their biggest challenge is the lack of local heat pump and refrigeration technicians; so, any time that maintenance is required from the manufacturer and travel costs tend to be high, as more time is spent by technicians traveling to and from Seward than actually working on the system.

Expected life

The life expectancy of newer heat pumps is still not entirely known, but 20 to 25 years is safe to assume for larger heat pumps. For smaller mini-split air-source heat pumps, life expectancy is probably closer to 15 years. Compressor replacement will likely be necessary after approximately 12 years in ground-source heat pumps, according to Andy Roe. Trane, the manufacturer of the large 90-ton heat pumps at the Alaska Sea Life Center, reports that the compressor bearing the lifespan of the units of 20 years is based on 40 000 total hours of operation at

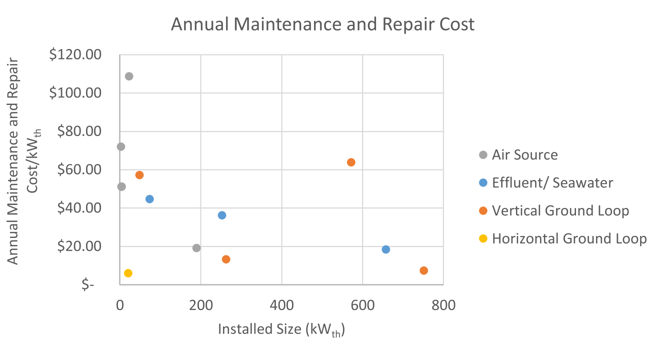

FIG. 2. Maintenance and repair costs per kW_{th} along with the system installation size are shown for 14 heat pumps around Alaska. These cost figures include the estimated cost of eventual replacement or refurbishment of the system; the approximate cost of system replacement in 20–25 years. These cost figures do not include the electricity needed to run the systems.

2000 h per year. Compressor overhaul will likely be necessary at 12–15 years at a cost of $30 000–$50 000.

Conditions for the greatest efficiency and the coefficient of performance

Heat pump efficiency is dependent on input temperature on the cold side of the unit. This is the outside air temperature for an air-source heat pump or the seawater temperature for a seawater-source heat pump. The compressors in the heat pumps must work harder to extract heat from colder fluids, as shown in Fig. 3. Warmer input temperatures lead to higher coefficients of performance.

A study by the Cold Climate Housing Research Center (CCHRC) on air-source heat pump performance around Alaska found that performance varied widely based on the heat pump model as well as on regional locations (Stevens *et al.*, 2015). Air-source heat pumps have reported operating ranges as low as −27 °C; however, below 17 °C, current technology is likely to be problematic. Cold weather heat pump technology continues to advance. Many participants in the study from the CCHRC reported that air-source heat pumps did not work on the coldest days. The authors of the study recommended that in Alaska, air-source heat pumps are paired with a backup heating appliance.

Ultimately, the economics of a heat pump are largely dependent on the cost of electricity and the cost of an alternate fuel source such as natural gas or heating oil. Heat pumps will be most economical in places with inexpensive electricity, expensive fuel oil, and conditions that lead to high coefficients of performance (Compare Home Heating Costs, 2017). In 2015, the CCHRC produced a two-page handout entitled "Could a ground source heat pump work for you?" This document explains that forced air—or in-floor hydronic heating paired with south-facing slopes and cheap electricity, relative to the cost of the alternate fuel type—could make a ground-source heat pump an economical heating option (Garber-Slaght and Rettig, 2015). This scenario is common in Southeast Alaska where inexpensive hydropower and expensive imported heating oil can make heat pumps a cost effective option. Alternatively, switching from electric resistance heating to a heat pump is nearly always cost effective.

Diesel offsets

Using annual electrical energy consumption and the coefficients of performance reported in Fig. 3, an estimated diesel offset was calculated for these systems (see Table II). The following assumptions were used:

- Alternate heating source is a fuel oil-powered boiler
- One gallon of heating oil = 138 000 Btu
- Boiler operates at an efficiency of 85%

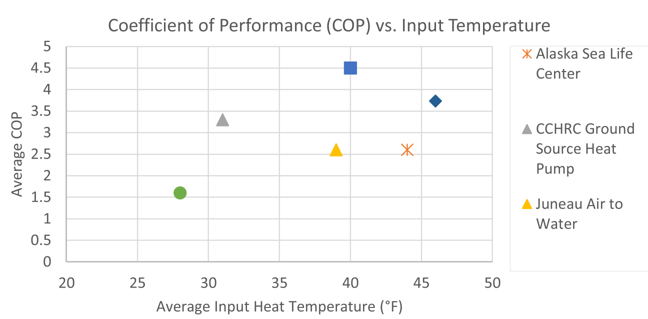

FIG. 3. Average coefficient of performance is plotted according to input temperatures for a variety of heat pumps in Alaska. Warmer input temperatures lead to higher coefficients of performance.

TABLE II. Approximate fuel offsets of heat pumps in Alaska.

Heat pump installations	Annual fuel oil offset (gallons)
Alaska Sea Life Center seawater heat pump	41 534
CCHRC ground-source heat pump	746
Juneau residential air to water	858
Wrangell utility office air-source heat pump	276
Dillingham air-source heat pump	26
Weller Elementary School ground-source heat pump	575

Levelized cost of energy (LCOE)

Using the levelized cost of energy (LCOE) calculator from the National Renewable Energy Lab (http://www.nrel.gov/analysis/tech_lcoe), we used a set of assumptions to calculate the LCOE for a range of conditions. Capital costs, capacity factor, and O&M costs were kept constant, while the coefficient of performance (COP) values were changed to demonstrate the effect that changing COP values have on LCOE. Cost assumptions are shown in Table III. These are middle-of-the-road costs, as observed in the systems reviewed in this study. Some systems such as the Alaska Sea Life Center system had lower costs, and other systems had higher costs. The LCOE values ranged from $.083/kWh$_{th}$, with a COP of 3.5 and electricity at $.08/kWh$_e$, to $.221/kWh$_{th}$ with a COP of 1.5 and electricity at $.24/kWh$_e$ (Fig. 4). These LCOE values are equivalent to $2.85/gallon and $7.59/gallon of fuel oil, respectively, when consumed in a boiler with an efficiency of 85% (Fig. 5).

Cost curve over time

The number of different units installed varies in size, type, and location. There are not enough long term data in Alaska to show a change in the installed cost over time.

Transportation average

Heat pumps do not require any special transportation and can be shipped around the state as any other piece of equipment would be shipped; they are shipped to Alaska from Lower 48 and sometimes from outside the United States. Small mini-split air-source heat pumps, like those described in this study installed in Wrangell and Dillingham, weigh about 100 pounds.

Technology trends

Heat pump technology is improving as companies strive to develop more efficient heat pumps that function better in colder climates. In addition, advances with more efficient compressors and alternate natural refrigerants such as carbon dioxide, propane, and ammonia enable heat pumps to efficiently heat water to higher temperatures. This is attractive for space heating as well as in industrial process heating applications. In December 2015, the Alaska Sea Life Center installed four water-to-water heat pumps that use carbon dioxide as

TABLE III. LCOE calculation assumptions.

Capital cost ($/kW$_{th}$)	$2000
Capacity factor (%)	30
Fixed O&M ($/kW$_{th}$-Yr)	$20
Variable O&M ($/kW h)	$0.002
Heat rate/COP (Btu/kW h)	2274 (for COP of 1.5)
Fuel cost ($/MMBtu)	Varies with the electric rate

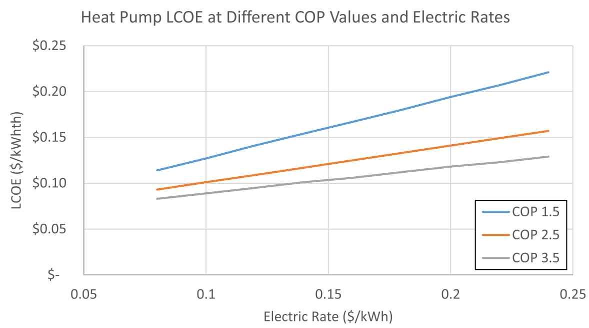

FIG. 4. Heat pump LCOE is plotted at different electric rates and different COP values using a constant set of assumed capital and O&M costs.

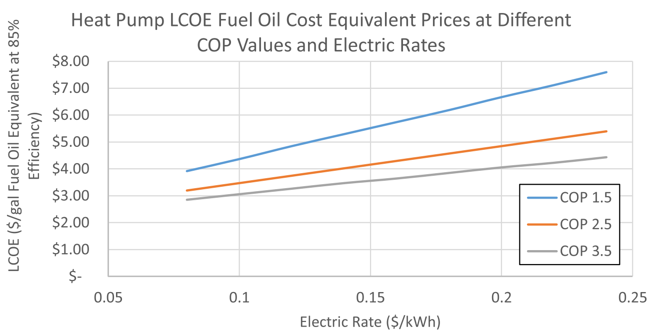

FIG. 5. This graph uses the same input data as Fig. 4. However, LCOE is shown as the equivalent cost of fuel oil when consumed in an 85% efficient boiler.

a refrigerant. This design compresses the carbon dioxide to a transcritical state at 2000 psi and enables hydronic fluid to be heated as high as 90 °C. The project demonstrates the integration of transcritical carbon dioxide heat pumps into an existing medium-temperature (70 °C) hydronic heating system in a large facility with both heating and cooling loads. The challenge of this emerging technology is that it requires higher refrigerant pressures, and the price of the packaged units is still significantly higher than that of conventional R-134a heat pumps.

CONCLUSIONS

Data from 17 heat pump projects in Alaska were reviewed as part of this study. These data indicate that ground-source systems show the widest range for installed cost/kW: from less than $2000/kW to over $12 000/kW. The same range is found for air-source heat pumps, which tend to be used for smaller projects. The smallest range of installed cost/kW is found for seawater-source heat pumps. Sea water sourced heat pump systems are typically installed where a reliable intake of seawater is already in place, and so, the intake cost is not included in these figure. All systems over 200 kW were either seawater heat pumps or ground-source heat pumps. The mean cost/kW of the systems studied is $5579. The average cost per installed kW of various types of heat pumps reviewed is as follows:

- Effluent/Seawater $2096
- Vertical Ground Loop $7613
- Horizontal Ground Loop $3036
- Air Source $10 359

The LCOE values ranged from $.083/kWh$_{th}$ for heat pumps with a COP of 3.5 and electricity at $.08/kWh$_{e}$ to $.221/kWh$_{th}$ with a COP of 1.5 and electricity at $.24/kWh$_{e}$.

The life expectancy of newer heat pumps installed in Alaska is still not entirely known but is probably 20 to 25 years. For smaller mini-split air-source heat pumps, life expectancy is closer to 15 years. Compressor replacement is typically needed sometime during the lifetime of the heat pump. On some larger units, a compressor overhaul could be necessary at 12–15 years at a cost of $30 000–$50 000.

Heat pump technology is improving as companies develop more efficient heat pumps that function better in colder climates. Some air-source heat pumps have operating ranges as low as $-27\,^{\circ}$C; however, in Alaska, a backup heating source is recommended during cold temperature air source heat pump operation.

In the correct environment, heat pumps are a viable technology for space and water heating in Alaska, especially where cheap electricity and expensive fuel oil or natural gas coincide with each other.

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