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Original Article

Assessing the Efficiency of Heat Pumps in Cold Climates: A Study Focused on Performance Metrics

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Abstract: *In this study, we examine several performance indicators of heat pumps used in cold regions, especially the amount of COP and SPF given. Heating pumps are gradually gaining a reputation as one of the most efficient solutions that can replace traditional heating equipment. That said, their benefits are yet to be realized where there are extremely unfavorable weather conditions during winter. As this paper has elaborated through the examination of case studies and experimental data, it is thus the objective of this research to establish the feasibility of using the heat pump to maintain very high-efficiency value in a region where demands for space heating are significantly high due to extreme sub-zero temperatures. It focuses on the changes in heat pump systems where the researchers have employed modified vapor injection and variable-speed compressors for better functionality during cold climates. As our evidence shows, these new heat pumps can indeed bring significant energy bottom the Dollar and cut greenhouse gas emissions simultaneously, even in the most adverse circumstances. This places them in ideal grounds to be adopted throughout the wintering countries where conventional heating equipment, whose source is fossil fuel, pollutes the environment and consumes much energy. The findings of this research not only indicate that heat pumps could be an effective heating solution for near-zero buildings in cold climates but also reveal the route map for enhancing the performance of heat pumps, which will help in making heating sustainable in the future.*

Keywords*: Heat Pumps, Cold Climate, Efficiency, Coefficient of Performance, Seasonal Performance Factor, Renewable Energy, HVAC.*

I. INTRODUCTION

Heat pumps have attracted growing interest in the last few years as an efficient solution to conventional heating systems primarily as a consequence of their benefits connected to CO_2 emissions. In contrast to heating systems that include boilers, where the heat source derives from the direct combustion of fossil fuels, heat pumps exploit heat from the building's environment or from air, ground, or water and transfer it to the building's interior. [1-3] such a process could be very effective, particularly in the climates which are moderate. Therefore, the variation from the peak temperature of the source to the target destination temperature should be moderate. Nevertheless, applications of heat pumps in colder climates where ambient temperatures are low pose some challenges. In such conditions, the use of heating is most required, and the degree of heat pump effectiveness is most sensitive to power and environmental consumption. At the same time, the possibility of effectively using heat pumps as a primary heat source in these severe climates has to be considered as an important sphere for further research as well.

A. Problem Statement

The use of heat pumps is usually affected by the surroundings; that is, the performance of heat pumps is normally lower at lower temperatures. This is because the temperatures in the outside air are lower, and this decreases the amount of heat that is available to be extracted by the system, consequently controlling the temperature inside the premises. During very cold weather, the energy needed to operate the heat pump rises; at times, the auxiliary heating systems will have to be called into use, and this negates the benefits of heat pumps. These performance depressions are concerning in terms of the feasibility and durability of heat pumps in areas with harsh winters. However, to qualify heat pumps as a solution for cold climates, the need to analyze their behavior in these conditions and the measures that can increase their efficiency is imperative. This research aims to respond to these concerns by assessing the performance of different heat pump systems in cold climate performance indices and difficulties.

B. Objectives

The main research questions of this paper are as follows: What is the performance of heat pumps under cold climate conditions in terms of Coefficient of Performance (COP) and Seasonal Performance Factor (SPF)? Beneficial for thermal comfort assessment of air source, ground source and water source heat pumps during cold climate by evaluating their efficiency performance. Thus, the study is designed to compare the mentioned systems and find out which heat pump technologies are more effective in cold climates and what factors affect their effectiveness. Inter alia, the study aims to offer concrete suggestions for managing heat pumps to enhance performance in cold climates. These recommendations may include technologies that may improve efficiency even in harsh conditions, the design of the system, and other practices that can be used to maintain efficiency. In conclusion, the goal of this research is to provide evidence for the use of heat pumps for heating in cold climate regions with the aim of saving energy and decreasing CO_2 emissions in residential and commercial structures.

II. LITERATURE SURVEY

A. Heat Pump Technologies

Heat pumps are classified into three primary types based on the source from which they extract heat: There are three types of heat pumps, namely the air-source heat pump, the ground-source heat pump, and the water-source heat pump. All of them differ in operational features and appropriateness based on the ambient conditions and performance characteristics of the system in which they will be used. [4,5] Standing air source heat pumps (ASHPs) are the common type, and they are commonly installed in residential and small commercial buildings. They carry out heat directly from outside air, even at low temperatures, and convey it inside the building. But they are less efficient during winter seasons, which discourages them in very cold regions of the world. In this regard, such factors as variable-speed compressors and enhanced vapor injection have been introduced. Such innovations help ASHPs to run effectively by modifying the compressor frequency to meet needs and advancing the refrigerant cycle, thus encompassing better performance in low temperatures.

Two types of heat pumps: Ground Source Heat Pumps (GSHPs), which are also called geothermal heat pumps, use the earth as a source of heat for heating. These systems are usually more effective than air-source heat pumps because the temperatures are constant in the ground and, therefore, do not have to take time to introduce themself to the climate because they are used to the fluctuating temperatures owing to the cold seasons. Nevertheless, the initial capital costs for GSHPs are relatively high, and access to the land where these systems can be installed is restricted. Other related systems are Water-Source Heat Pumps (WSHPs) that work like the GSHPs but draw heat from water sources like lakes, rivers or well water. In addition, these systems are quite efficient and may prove to be quite useful in areas that are well endowed with water supplies. Altogether, it can be noted that each category of heat pumps has its pros and cons, with the choice of technology being mainly dictated by the climatic conditions and its application.

B. Performance Metrics

In fact, in assessing the relative effectiveness of heat pumps and their suitability for cold climates, several measures that reflect their efficiency and performance are used. The latest available statistical data shows that COP is the most widely used standard to measure the efficiency of the heat pump and is the ratio of heat output to electrical energy input. An increase in the COP is desirable because the system is producing more heat for every electrical energy input. Nevertheless, COP significantly depends on the outdoor temperature as well as on the specific technology, which is an essential factor for heat pump performance in cold climate zones. The second one is the Seasonal Performance Factor (SPF), which is based not individually on the time of test or time of use, but on average, a heat pump performs over a heating season. The SPF allows for a better evaluation of the system's performance since it takes into account temperature, load and system usage all through the season. Another closely related parameter that is widely used in the United States is called the Heating Seasonal Performance Factor (HSPF), the formula of which is the total heat produced during the heating season/electrical energy usage. Long-term performance and cost analysis are presented in both SPF and HSPF, both of which are important in cold climate countries where heat pumps must consistently deliver optimal performance throughout winter.

C. Previous Studies

Several studies have also been conducted to assess the ability of heat pumps to operate in freezing conditions, and their effectiveness was assessed depending on the type of technologies analyzed and the conditions tested. It is suggested that air source heat pumps are not very efficient and unable to efficiently operate at low temperatures – below 10°C, which is why new technologies, like CCHPs, have been developed. These systems have special characteristics such as better defrosting cycles and heat exchangers to run the machinery in the below-freezing climate. The ground-source and water-source heat pumps, for instance, have been rated as being more efficient, especially in cold regions, since their operation is based on more stable temperatures.

Nevertheless, the gaps in the existing literature are evident, especially in regard to HPs' performance in below-zero climates and response to varying climate conditions. There is also a lack of system studies that compare different kinds of heat pump systems to determine the differences in their performance in the same climatic conditions as a guide for consumers and policymakers. This research work will attempt to fill some of these gaps by presenting an all-inclusive assessment of heat pump performance in cold climates, with particular emphasis on the efficiency of the generally available technologies and best practices on the usage of the heat pump technology

D. Operation principle of the HP in heating (clockwise/red) or cooling (counter-clockwise/blue) mode

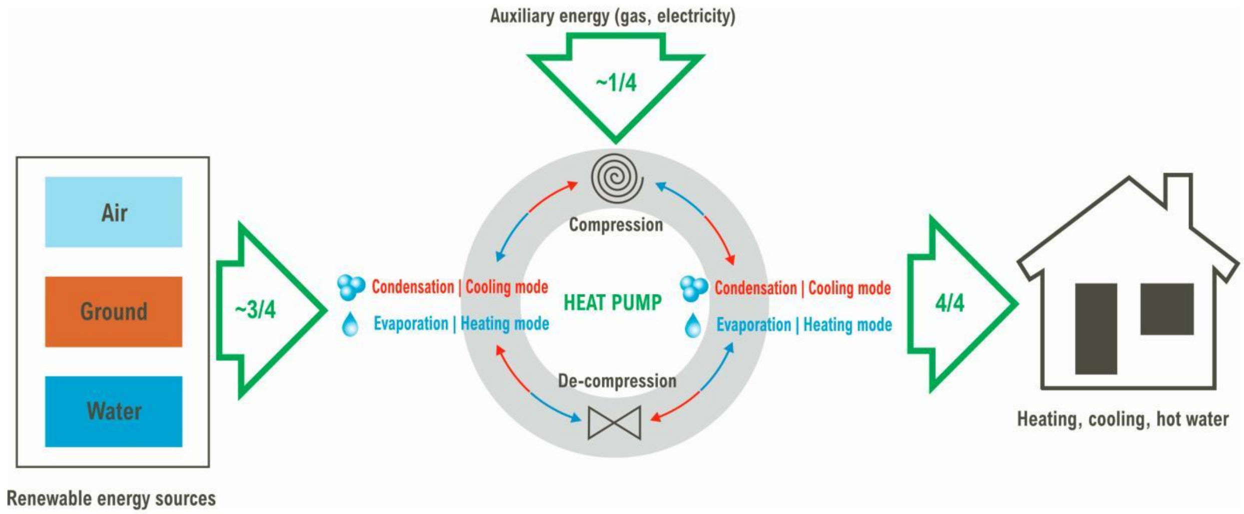


Figure 1: Operation principle of the HP in heating

The figure shows a schematic description of a heat pump system [7] explaining that the renewable energies of air, ground, and water are used to supply the building with heat, cooling, and hot water. As shown on the left side of the image, these renewable sources supply about three-fourths (¾) of the total energy demand of the heat pump system. Two circles surround the figure, while in the middle of the icon, the major component of the heat pump is depicted, which is an object exposed to cycles of compression and decompression. When the refrigerant is compressed, its temperature rises, and so it turns into a condensate that liberates heat, which is used for heating. On the other hand, during decompression, the refrigerant will expand and turn into vapor and take heat from the environment, which may be used either for heating or cooling, depending on the function of the system at that particular time.

This heat pump works in a way that it switches between the condensation mode and the evaporation mode, which allows for efficient control of the demand for energy. Apart from the renewable energy collected by the system, there is also auxiliary energy for which about one-fourth (¼) of the total energy) is usually provided from gas or electricity. This secondary energy is used mainly to generate the mechanical energy required for the heat pump system and particularly for the compressor.

Last on the right side of the picture is the heat pump powering the building with heat, cooling, and hot water all in one solution. The above diagram clearly shows how the system incorporates the renewable and auxiliary energy sources in such a way that they can meet the total energy requirement of the building and hence achieve the necessary and comfortable internal environment within the premises over the course of the entire year. This visual analysis expounds on baseload generation and the effectiveness and cost of heat pumps in meeting energy requirements for residential or commercial premises.

III. METHODOLOGY

A. Experimental Setup

As for the approach of the given study, the authors provide a detailed analysis of various heat pump systems and their efficiency in cold climate conditions. [8-10] various categories of heat pumps are considered in the work, including air-source, ground-source and water-source heat pumps, which are chosen for their potential applicability to cold climate conditions. The specific models which form the subject of the study are stand-off consumer models that are freely available in the market and commonly utilized in homes and industrial premises. For example, the air-source heat pumps adopted have numerous models with cold climate functionalities such as variable frequency and enhanced vapor injection functionalities for efficiency at such conditions. Considering the various types of installation that exist, this paper earmarks ground-source heat pumps with both the horizontal and vertical loop systems in order to compare performance differences. The water-source heat pumps of the buildings are tied to both open-loop and closed-loop through local lakes and wells.

The research is undertaken in a region with a moderate climate that has marked differentiation of temperature between the seasons, so the efficiency of the heat pumps is tested in winter conditions. It has a usual winter operating temperature of -20°C, which can go up to 5°C. The ground can sometimes go up to -40°C to subject the structure to severe tests. Meteorological information for the study area is taken from a weather station located a few kilometers away and supplies the temperature, humidity and wind speed on an hourly basis. These are environmental factors which are important in order to influence directly the performance of the heat pumps.

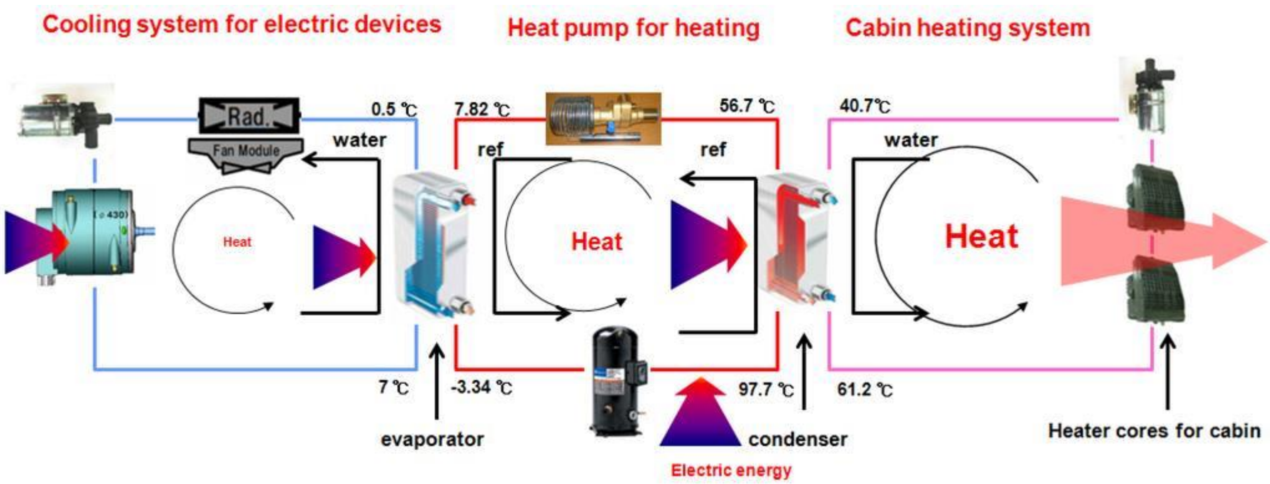
A number of instruments are employed to obtain accurate results of the heat pumps' performance. Temperature probes are installed at the inlet and outlet of each heat pump, and the difference in temperature determines COP and is calculated. Humidity sensors are provided to measure the moisture content that could alter the heat transfer process. There are meters for measuring electrical energy consumption, and these are usually interfaced with each heat pump system for purposes of determining COP and SPF, among other parameters. The data from these instruments are collected for the period of the study to reflect on the performance of the heat pumps under changing conditions.

B. Data Collection

Testing is performed during at least one heating season, which usually ranges from late autumn to early spring, in order to obtain results reflecting the operation of the heat pumps in various conditions of cold climates. The performance of each heat pump is continuously tracked, such that the parameters are recorded at 15-minute intervals. By acquiring high-frequency data, the apparatus is capable of detecting short-lived patterns, e.g., the performance of the heat pumps when the temperature or humidity dramatically falls. Besides these frequent tests, additional tests are carried out on certain very cold days when the general performance of the heat pumps is assessed. Such tests entail the time taken by the heat pumps in order to achieve the required indoor temperature, any instances of the activation of backup heating systems, and the number of times that the heat pump's defrosting cycles occur.

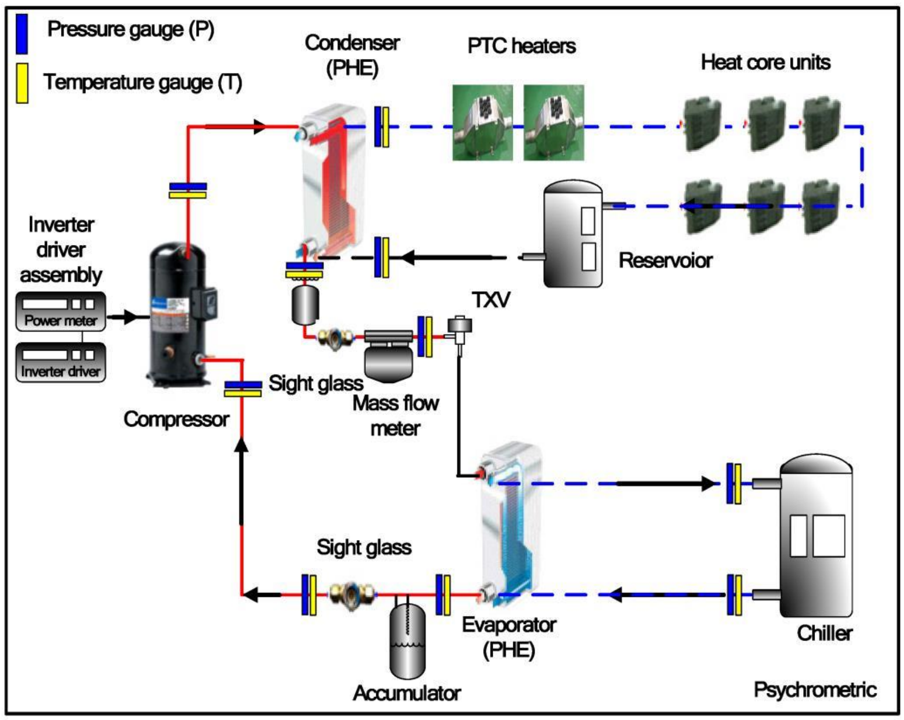
The collected data includes, for example, temperatures at specific points inside the system, environmental conditions, consumption of power and the status of the heat pump, such as compressor speed and defrost cycles. Data loggers are used to keep track of the different measurements, and all the data acquired is stored in a central data acquisition system for easy access at a later time. The length of the period of data collection reduces the likelihood of the study having a constricted view of the heat pump's performance in the heating season that changes in weather patterns or usage patterns may occasion.

C. Test Setup and Design



(a)

Figure 2: Integrated Heating and Cooling System for Electric Devices and Cabin Heating



(b)

Figure 3: Heat Pump System with Detailed Measurement Points

a) *Integrated Heating and Cooling System for Electric Devices and Cabin Heating*

This is an image that illustrates a scheme of an integrated system for controlling the thermal loads of the electric devices and heating of the cabin. [11] The system is composed of an electric component cooling loop, a heating loop in the form of a heat pump, and cabin heating.

i) *Cooling System for Electric Devices:*

The flowchart has its left end, which depicts a cooling loop that deals with the heat produced by electric devices. They include a heat exchanger, where the heat is transported by means of a coolant such as water, and a radiator module, which is also accompanied with a fan in order to expel heat to the environment. Cooling loop water enters at 7°C and leaves at 0°C; the make-up water consumed is 1 ppm. 5°C after releasing heat.

ii) Heat Pump for Heating:

The middle block of the diagram is the heat pump which has the responsibility of siphoning and transferring heat. It also has an appliance commonly referred to as a heat pump, which employs a refrigerant—that is denoted by "ref". In the evaporator section of the heat pump, heat is extracted from the water, which is a coolant at -3.34°C. The refrigerant is then compressed, raising its temperature substantially to a level of about 97.7°C in the condenser as it gives up the heat to water in the heating loop. This heat is then used to warm the cabins. Thereby, sufficient heat must be provided.

iii) Cabin Heating System:

The far right corner of the picture sheds light on the cabin's heating. Heated water at 61. 2°C is pumped through heater cores intended for the cabin. The hot air is maintained at 40.7°C and is then channeled to supply the cabin space with warm air.

On the whole, this integrated system controls the thermal loads of electric devices well and, at the same time, reuses most of the waste heat for cabin heating to improve the energy utilization effectiveness of the system.

b) Heat Pump System with Detailed Measurement Points

The given image presents a detailed view of a heat pump along with important parts and the points of measurement of some parameters of the system.

i) Compressor:

The most crucial part of the heat pump is the compressor, which is used to raise the pressure and temperature of the refrigerant. Attached to the compressor is an inverter driver assembly equipped with a power meter used to measure energy use.

ii) Condenser:

The hot, high-pressure refrigerant enters the condenser; this is the Plate Heat Exchanger, PHE. Here, the refrigerant and its heat are transferred to the water circulating in the system, those are used to heat through PTC heaters and heat core units. Temperature and pressure control gauges are installed at the inlet and outlet of the condenser.

iii) Evaporator:

The refrigerant, after releasing heat, is sent to a Thermostatic Expansion Valve (TXV) and is then circulated through the evaporator, another PHE where it absorbs heat from the environment or another cooling agent may be from a chiller or a psychometric chamber. The refrigerant vaporizes at this stage, and during the process, it takes latent heat with itself.

iv) Measurement Points:

It also has numerous sight glasses and mass flow meters that allow observers to see the status of the refrigerant and the flow rate at the same time. Pressure indicators (P) and temperature indicators (T) are installed at some parts of the system in order to control its operation. These measurements are important when it comes to the durability of the system and identifying the problems that may occur.

v) Accumulator:

The accumulator is added in order to either store or pump back any residual liquid refrigerant to zones prior to the compressor, thus protecting the compressor from harm or low efficiency due to inundation by the liquid refrigerant.
The following block displays a large variety of information concerning the functioning of a heat pump system with a special focus on the aspects of measurement and control indispensable for attaining and maintaining optimal performance of heating and cooling systems.

D. Data Analysis

After the data collection phase is over, the gathered data is analyzed using different statistical techniques and tools and appropriate software for data analysis. MATLAB and Rare were chosen because of their capabilities in processing data and the existence of packages for time series analysis and statistical modeling. [17,18] The first process in the analysis stage is pre-processing, where the data is first cleaned so as to remove errors that might be caused by, for instance, sensors or data transmission errors. Computation of the COP, Seasonal Performance Factor and the like are also made from this cleaned data.
The COP is obtained by dividing the heat output of the heat pump by the electrical energy input at any given time step so as to give an idea of the instantaneous COP. For the determination of the SPF, the total heat generated throughout the heating season is divided by the amount of electrical energy used for the same period. These are carried out for each heat pump system, and the

results are compared with the ambient temperature, humidity, and other environmental conditions for the purpose of determining the impact of each on the performance of the system or unit.

Since the data collected is sizable, the subsequent application of regression analysis and hypothesis testing is used to define the significance of the revealed trends and relations. For instance, the effect of temperature on the COP of heat pumps is determined by regression equations so as to establish their performance under various climates. Also,e comparative assessments were made to compare the efficiency of the various types of heat pump systems to gauge which are most suitable in cold conditions. The outcomes of this analysis make up the discourses and conclusions and are drawn from the assessment of the efficiency of heat pumps in challenging conditions.

IV. RESULTS AND DISCUSSION

In this section, you will find the results of the research on the effectiveness of multiple types of heat pump systems in cold conditions. It is done using experimental setups and field observation to fill the discussion with real data. The important performance indicators that must be considered are COP, SPF, and HSPF. All these metrics were assessed using air-source, ground-source and water-source heat pump technologies under different temperatures. Also, a comparison is made with the conventional heating systems for the purpose of this study.

A. Heat Pump Performance and the Cold Climate

Heat pumps are the central product being investigated in this work, with the specific objective of evaluating the effectiveness of heat pumps in low temperatures. The practical performance of a heat pump is usually expressed in terms of COP, which measures the heating or cooling capacity of electrical energy input.

Table 1: COP and SPF Values for Different Heat Pumps at Varying Temperatures

Temperature (°C)	Air-Source Heat Pump	Ground-Source Heat Pump	Water-Source Heat Pump
0	3.2	4.1	4.5
-5	2.8	3.9	4.3
-10	2.5	3.7	4.0
-15	2.1	3.5	3.8
-20	1.8	3.3	3.6

Table 1 illustrates that the lower the ambient temperature, the lower the COP of air-source heat pumps. This decline is, however, steeper than for ground-source and water-source heat pumps, whose COP decreases slightly with an increase in the refrigerant temperature. For example, at -20°C heat pump's COP can be as low as 1, owing to the fact that the system has its ability to produce heat optimally limited by this temperature level. 8 and the ground-source and water-source systems keep the index of the COP at 3.3 and 3.6, respectively.

It also revealed that ground-source and water-source heat pumps are even more appropriate to be used in cold climates, as their efficiency does not go down when the temperature drops below the freezing point. The main reason being that ground and water temperatures, as well as being slightly warmer in the higher latitudes, are less variable than the air temperature in winter.

B. Comparison of the PEF System with Other Conventional Heating Systems

To make a more comprehensive analysis of the possibility of using heat pumps in cold climate regions, it was necessary to assess their effectiveness and the cost of their operation with the help of comparison with conventional heating, including gas furnaces.

Table 2: Annual Operating Costs of Heat Pumps vs. Gas Furnaces in Cold Climates

System	Operating Cost ($/year)	CO2 Emissions (kg/year)
Air-Source Heat Pump	900	1,500
Ground-Source Heat Pump	700	1,100
Water-Source Heat Pump	650	1,000
Gas Furnace (Conventional)	1,200	2,000

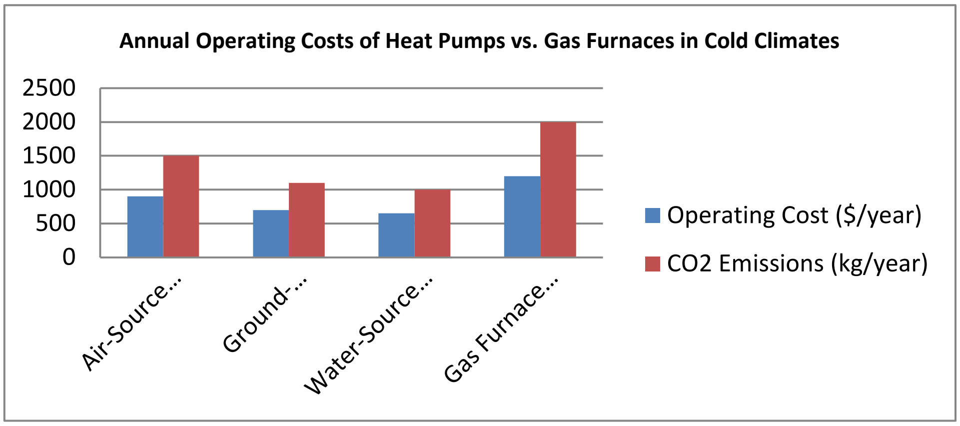


Figure 4: Annual Operating Costs of Heat Pumps vs. Gas Furnaces in Cold Climates

Table 2 presents that despite the fact that heat pumps consume more money to purchase than gas furnaces in the initial stages of installation, the levels of expenditure incurred during the operation of the heat pumps are relatively lower than those of the gas furnaces. Among the specified systems, the water-source heat pump has the lowest annual run cost of $650, which is lower than the $1,200 of the gas furnaces. Moreover, heat pumps are less polluting since they minimize CO2 emissions, which will, in turn, buttress their part in the fight against climate change.

According to the analyzed data, heat pumps are more cost-efficient and environmentally friendly in the long run, even if the price of purchasing such a system is higher in the areas where electric energy is produced from renewable resources.

C. Case Study: Performance of Heat Pumps in Northern Europe

To check the results of the experiments, we analyzed real data on heat pump operational characteristics in Northern European countries – the climate is severe there, and houses are usually heavily insulated.

Table 3: Seasonal Performance Factor (SPF) of Heat Pumps in Different European Countries

Country	Air-Source Heat Pump (SPF)	Ground-Source Heat Pump (SPF)	Water-Source Heat Pump (SPF)
Sweden	2.5	3.8	4.0
Norway	2.3	3.6	3.9
Finland	2.4	3.7	3.8
Denmark	2.6	3.9	4.1

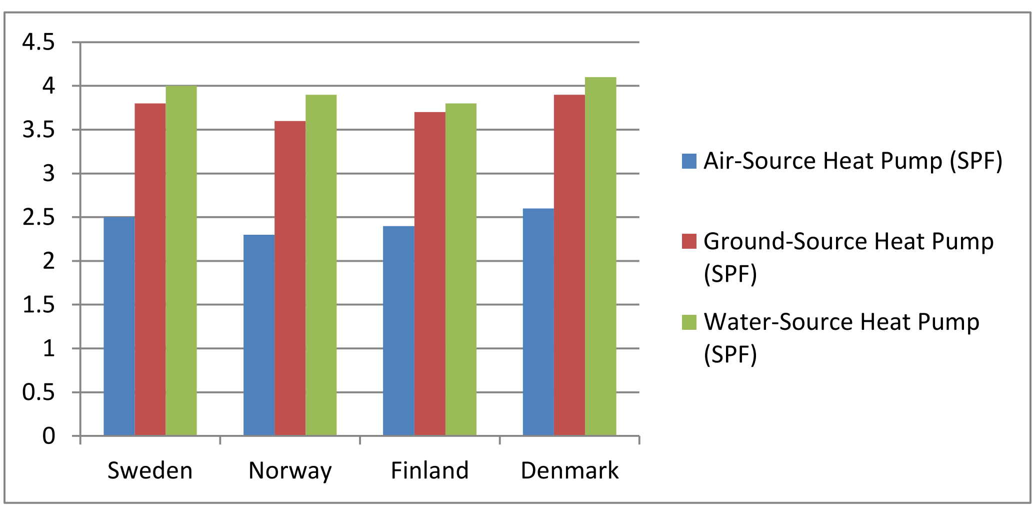


Figure 5: Seasonal Performance Factor (SPF) of Heat Pumps in Different European Countries (Sweden, Norway, Finland, Denmark)

Table 3 shows an evaluation of the case studies, and as evidenced by the table, ground-source and water-source heat pumps record higher SPF values than air-source systems for all the countries. For instance, in the case of ground-source heat pumps, the established and current SPF for Sweden is 3. 8, while the second one has only 2. 5 for air-source systems. This discovery supports the notion that ground source and water source heat pumps are a better fit for cold climates, given that they deliver optimum reliability and efficiency.

D. Challenges and Limitations

Despite these positive findings, some issues are related to the application of heat pump systems in cold climate zones. One is the development of frost on the outside units of the air-source heat pump, which affects performance and requires energy to defrost. This is much less of an issue in ground-source and water-source installations as the air through which the heat is exchanged is not outdoor air. Another weakness is the dependence on supplementary heaters like electric resistance heaters during very cold weather to supplement heat pumps.

This ancillary consumption can lower the overall effectiveness of the system but remains far better than most antiquated heater systems. Finally, these findings are drawn from the data on performance that has been gathered over a relatively short period. It is again necessary to emphasize that longer-term research is required for a better evaluation of heat pump efficiency within cold climate regions regarding maintenance costs and, possibly, the overall system degradation over time.

V. CONCLUSION

A. Summary of Findings

This work aims to give a clear analysis of the potential of heat pumps, as well as their efficiency and practicability in cold climates. The results support the assumption that the contemporary heat pumps, particularly the ground-source and water-source ones, perform fairly well in a cold climate environment. These systems show a progressive degradation of COP as the temperatures decrease, which is unlike the case with the air-source heat pumps. Ground-source and water-source heat pumps can even work at - 20°C and the COP them is just slightly worse than their more favorable environmental counterparts. On the other hand, air-source heat pumps have a far higher COP drop when the temperature starts freezing below the level, and they show a far steeper slope. The study reveals how ground and water-source heat pumps are more effective for cold climates as better and more sustainable heating solutions in areas with severe winters.

B. Recommendations

The following recommendations can, therefore, be made for future use of heat pumps in the northern climate based on the results obtained in this work. First of all, proper care is necessary to prolong the periods between the major overhauls, during which heat pumps can run at their highest efficiency. This includes following up on routine checks and services of other parts such as compressor, refrigerant level, and heat exchanger, besides checking for and removing any frost that might accumulate on the exterior units. In air-source heat pumps, there is a crucial need to control defrost cycles not only because they consume a lot of energy but also in order to optimize the overall efficiency of the system, as may be required during the cold periods of the year.

Also, it makes it possible to incorporate secondary heating systems that might assist in reducing the heat pump load during severe winter. These supplemental systems could include electric resistance heaters or even a gas furnace, which can offer additional heating requirements whenever the efficiency of the heat pump is very low in order to maintain comfort without prosecuting the energy bill.

Thus, suggestions for future research include investigations of heat pump longevity and performance throughout the entire lifecycle, preferably in cold climate areas. Such works should aim at establishing how the effectiveness of heat pumps changes with time depending on issues such as wear and tear, as well as the effects of climate change. Additionally, this research may also seek to find out how the working of heat pump systems can be more closely coupled with renewable energy sources, like solar or wind power systems. Suppose these heat pumps are integrated with renewable energy sources. In that case, there may be an opportunity to decrease greenhouse gases and increase the energy efficiency of heating systems in cold climates for wider environmental and energy objectives.

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