Feasibility and Economic Viability of Heat Pumps in Energy-Efficient Applications

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Abstract. Energy-saving techniques, such as the implementation of efficient engineering equipment, play a crucial role in reducing energy consumption within buildings and facilitating of a transition towards a low-carbon energy future. In this context, this paper briefly introduces the principle of heat pumps, along with an examination of the diverse circumstances in which different categories of heat pumps can be effectively employed while analyzing energy efficiency, economic considerations, as well as environmental implications. The adoption of heat pumps has been widely recognized as a means of achieving energy savings in comparison to the installation of conventional boiler/chiller systems, resulting in evident environmental effectiveness and substantial reduction in emissions. This paper examines the performance of several heat pump systems under diverse climatic situations and presents illustrative instances of effective implementation. Heat pumps tend to have higher initial costs but low maintenance and long lifespan. This paper also examines the remaining challenges for the broad deployment of heat pumps. Costs, policy, scientific limitations, and market dynamics challenges exist, which could potentially obstacle. The paper also included the prospective trajectory of heat pumps, with a notable emphasis on the integration of solar energy as an emerging trend, with the inclusion of solar energy being highlighted as a prospective trend. This paper aims to enhance comprehension of the feasibility and economic soundness of heat pumps.

Keywords: Heat pump, air-source heat pump, energy saving, climate change, ground-source heat pump.

1. Introduction

Heat pump systems provide energy-efficient and cost-effective options for capturing heat from a range of sources, which can then be utilized across a diverse array of industrial, commercial, and residential settings in the heating season as well as the cooling period. The roots of heat pump technology can be traced to 18th-century science, which evolved from refrigeration technology. In 1852, Lord Kelvin first proposed a notion pertaining to the heat pump, suggesting that a "reverse heat engine" may serve the purpose of both cooling and heating [1]. They gained prominence in the 1930s with ongoing technological advancements. With growing concerns about the cost of fuel and global warming taking center stage around the world, heat pumps have been resurrected for their ability to mitigate greenhouse gas emissions and lower energy usage in contrast to traditional systems for heating and cooling. Heat pumps present a practical solution to achieve a low-carbon energy future driven by their energetic, economic, and environmental benefits.

In recent years, there have been numerous studies focused on aspects such as effectiveness, the ability to reduce carbon footprints, and the method of integration with renewable energy sources of heat pumps. However, there has been a relatively restricted investigation into the economic viability of heat pumps. This paper aims to fill the existing gap by offering a thorough understanding of the role heat pump technology plays in promoting sustainable development. This study seeks to provide insights that can benefit policymakers, engineers, and decision-makers, fostering the widespread adoption of heat pump technology and facilitating a win-win scenario for both economic and environmental sustainability.

This paper briefly introduces the concise overview and diverse classifications of heat pumps. It conducts an analysis of their energy efficiency, economic considerations, and environmental impact.

This paper also identifies the obstacles and hurdles that hinder the extensive implementation of heat pumps in the market and provides recommendations for further development.

2. Heat Pumps

2.1. Fundamentals of Heat Pumps

The core mechanism of heat pump functionality is thermodynamics as well as heat transfer. Heat pumps employ technology that is akin to the mechanisms utilized in refrigerators or air conditioning systems. They are designed with the purpose of extracting thermal energy from various sources (the heat source), such as the ambient air, geothermal reservoirs, adjacent sources of water, or waste heat generated by industrial processes, and transferring it to another (the heat sink).

Heat pumps are thermodynamic devices that utilize a refrigeration cycle to facilitate the transfer of heat from an area characterized by a cooler environment to a region characterized by a warmer environment. The closed-loop refrigeration cycle incorporates four components, as depicted in Fig. 1. The refrigeration cycle is based on the utilization of a volatile liquid known as a refrigerant, which experiences phase transitions through the processes of compression and expansion, leading to the release and absorption of latent heat. The heat pump compresses the refrigerant to make it heated on the side that needs to be heated up and reduces pressure on the side that absorbs heat.

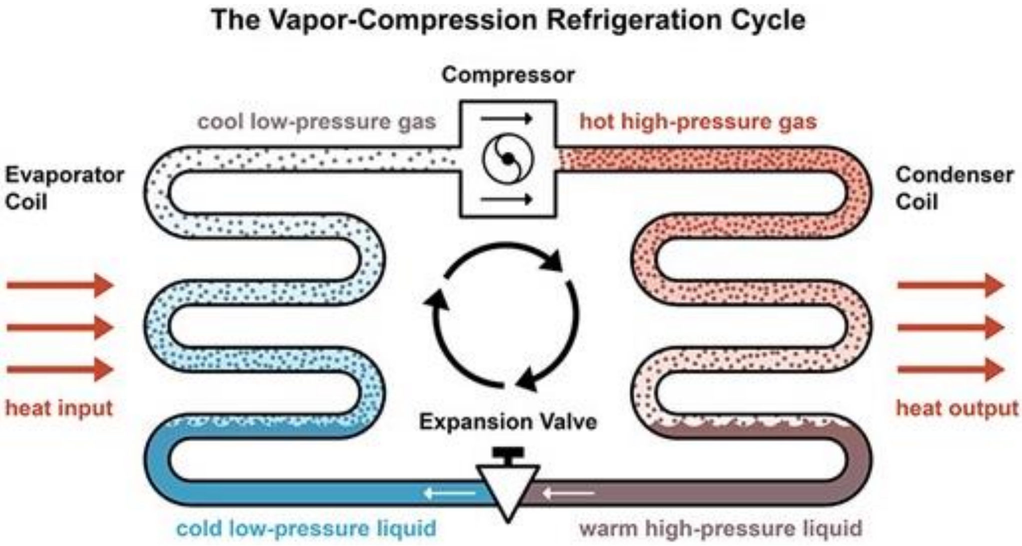

Figure 1. Schematic of the refrigeration cycle. https://www.aelp.com/Energy-Conservation/Heat-Pumps

2.2. Types of Heat Pumps

Heat pumps are categorized according to the source from which they extract or release heat. The two predominant categories of heat pumps commonly found are air-source and ground-source. Various types of systems will be introduced, each possessing distinct features and advantages, catering to different application scenarios.

2.2.1. Air-source heat pump

Air source heat pumps (ASHPs) are noteworthy for their widespread application in both residential and commercial settings. Compared to ground-source heat pumps, the land area necessary for ASHPs is considerably smaller. The utilization of ASHPs has the potential to exert a significant influence on the electrification of residential heating, in particular the context of retrofit initiatives targeting older residential properties located in urban regions [2, 3].

2.2.2. Ground-source heat pump

Ground-source heat pumps (GSHPs), alternatively mentioned as Geothermal heat pumps (GHPs), provide an innovative and ecologically sustainable approach to building heating. GSHPs consist of three primary systems, ground loop system, distribution system, and earth connection [4]. GSHPs exhibit suitability for various buildings and have utility in projects that prioritize the mitigation of environmental impacts [5].

2.2.3. Water-source heat pump

Water-source heat pumps (WSHPs) are a type of heat pump technology that uses a water body, such as a well, pond, lake, or river, as a medium for heat exchange. WSHPs produce fewer carbon emissions and offer substantial cost savings in comparison to air-source heat pumps [6]. It is mainly limited by water source availability and storage requirements.

2.2.4. Solar-assisted heat pump

Solar-assisted heat pumps (SAHPs) integrate advantageous characteristics of heat pump technology and thermal solar panels. The solar thermal panel functions as the primary heat source operating at low temperatures, providing heat to the heat pump system. This arrangement allows for a better COP to be achieved. However, there are still several significant challenges and gaps that need to be addressed in this field, such as poor energy performance at low ambient temperatures [7].

3. Energy Saving Potential

Heat pump technology has great potential to lower energy usage and associated operating costs. The implementation of heat pumps can result in energy savings exceeding 30% when compared to a traditional boiler/chiller system installation [8]. By utilizing a heat pump design, the water heater's total efficiency can be enhanced to at least double that of regular electric water heaters typically employed in the United States [9]. Additionally, heat pumps possess the capability to enhance the energy efficiency of numerous industrial operations by effectively utilizing waste heat and converting it into useful outputs [10]. Heat pumps have the capability to retain waste heat by catching it and enhancing its temperature or quality, rendering it appropriate for utilization in further stages of the industrial process. This approach helps to maximize energy utilization and reduce overall energy waste in industrial operations.

Heat pumps typically can achieve Coefficient of Performance (COP) values of 2.5 or higher, indicating their capacity to generate heat energy that is 2.5 times greater than the electrical energy they consume. If electricity is the only option, this will lead to substantial energy savings compared to resistance-based electric heating systems. Heat pumps have optimal efficiency in regions characterized by moderate to warm climates. Air-source heat pumps, for example, might experience reduced efficiency in extremely low temperatures due to a fall in COP. This decline in COP is mostly attributed to the rise in temperature lift across the compressor. Geothermal heat pumps (GSHPs) can tackle the efficiency challenge due to stable underground temperatures.

4. Economic Analysis

Heat pumps typically have higher initial costs in comparison to traditional systems, especially in the context of GSHPs. Nevertheless, it is worth noting that they have little maintenance expenses and a lifespan of over two decades while delivering dependable and eco-friendly heating solutions [5]. The research demonstrates that ground- and air-source heat pumps have lower annual operating expenses compared to boilers and air conditioners, with costs ranging from 20% to 45% and 56% respectively [11]. Based on the findings presented in reference [12], the payback period for ASHPs in Norway is determined to be 8.088 years. The payback period for GSHP that utilize borehole heat exchangers (BHE) is determined to be 9.936 years and the payback period for GSHP systems employing heat pumps and energy heaps built vertically into the earth is estimated to be approximately 7.941 years. The specific period of payback is influenced by various factors, including energy efficiency, energy prices, and subsidy level.

Geothermal heat pump systems require higher costs and necessitate technical expertise for the construction of boreholes, compared to ASHPs. This notable disparity serves as a compelling incentive for individuals to opt for ASHP over GSHP [12]. According to the European Heat Pump Association, 80.1% of all heat pumps on the market are of the air-source type [13]. However, GSHP tends to exhibit higher COP than ASHP because of the stable underground temperatures, allowing it to be more sustainable and cost-efficient in terms of long-term performance. Solar-assisted heat pumps can achieve higher COP; however, the integration of solar technology is anticipated to result in higher upfront expenses and subsequently, elevated life cycle costs. Additionally, the utilization of electricity can significantly reduce reliance on gas and other fossil fuels, leading to mitigating the impact of rising costs of fossil fuels. With the significant increase in gas prices, the demand for heat pumps in Europe has significantly increased in response to the disruption of the Russian gas supply caused by the conflict in Ukraine.

5. Sustainability and Environmental Impact

It is generally accepted that heat pumps possess the ability to substantially mitigate carbon footprints and combat climate change. The environmental benefit can be concluded as the absence of emissions and renewable energy integration. The environmental impact of private investments and government subsidies in favor of GCHPs demonstrates significant efficacy [14]. The reduction in emissions ranges from 13 to 216 grams of CO_2 per year for every euro expended. Hybrid configurations can enhance this by a range of 30% to 81%, although incentives decrease with slightly smaller CO_2 reductions. GSHPs have been seen to exhibit a significant reduction in primary energy consumption ranging from 33% to 75% and reduce CO_2 emissions by 27% to 56% in contrast to traditional heating and cooling systems [14].

The heat pump's operational fluid is referred to as refrigerant, which is often associated with greenhouse gases or ozone-depleting substances. There is a risk that the refrigerants used in heat pumps could leak into the atmosphere, damaging the ozone layer, and contributing to detrimental environmental pollution and global warming. GSHP typically has a quantity of 2 kilograms of hydrofluorocarbons (HFCs), which are recognized as potent glasshouse gases. Hence, the proper maintenance and routine inspections of the heat pumps are critical. There have been expressed concerns regarding the compatibility of Ground-source heat pumps with groundwater resources. One of the primary concerns associated with the transfer of pollutants is the potential for these contaminants to utilize well holes as pathways to previously isolated subsurface aquifers, especially those that serve as sources of drinking water [15]. The anti-freeze compounds contained in BHEs (borehole heat exchangers) present the possible release of such compounds into groundwater. To mitigate this danger, it is recommended to use Propylene glycol as an anti-freeze component where necessary [16]. A substantial quantity of research focused on the advancement of the development of novel refrigerants that possess low environmental impact and the capacity to further enhance their performance has been undertaken in the last several years. One such example is the refrigerant mixture R290/R600a/R13I1, which achieves an annual average COP that is about 6.2% higher than with R134a. Additionally, this blend possesses a low global warming potential (GWP) as well as lacks any ozone depletion potential (ODP) [17].

The utilization of heat pump technology is experiencing an upward trend, albeit with limited market penetration. Despite the positive environmental impact and cost-effectiveness of heat pumps, the time it takes to recoup the initial investment remains quite long. This highlights the need for government assistance to promote wider adoption and implementation, while uncertainty in policy, lack of definitive heat decarbonization strategies, and limited technology adoption are key impediments [14]. The potential impediment lies in the uncertainties pertaining to fuel and carbon prices, and the costs linked to renewable energy sources [6]. The high initial expenditures and space requirements for installation should also be noted as significant impediments.

Heat pumps are still a strong contender in the realm of sustainable development and the shift towards low-carbon alternatives. In a scenario aligned with the global climate target of reducing the global temperature increase by 1.5°C, the growth rate of heat pumps is expedited, resulting in a roughly threefold increase in their capacity by the year 2030 and projected to account for a quarter of the overall heating share [18].

The incorporation of solar technology with heat pumps are the recent focus of several research studies due to this combination enabling the system to achieve a higher COP, hence indicating its potential as a promising avenue for heat pump development. By adjusting the connection modes of ASHP and solar hot water (SHW) in accordance with the external weather, combining ASHPs with a solar-powered water heating system can achieve significant energy savings [19]. The integration of solar and air energy in a combined heating system addresses the limitations of the ASHP's efficiency in cold conditions while compensating for the intermittent nature of solar collectors as the main source of energy [19]. A system was tested for a heat pump used for typical DHW production of a dwelling typically occupied by a family of four. It was noted that the system's overall COP can reach 9 when combined with photovoltaic (PV) systems [20]. This combination enhances the overall performance of the heating system while maximizing renewable energy contribution.

6. Conclusion

The primary aim of this study is to investigate the sustainability, financial viability, and environmental benefits of heat pumps, which provide insights into the existing state of heat pumps and identification of the main barriers. Compared to ASHPs, GSHPs tend to have efficiency challenges due to stable underground temperatures. Heat pumps typically have higher initial costs, especially when considering GSHPs, but they have little maintenance expenses and a long lifespan. Heat pumps have great potential to significantly reduce carbon footprints and combat climate change, but there are still concerns about refrigerant leaks and the compatibility of GSHPs with groundwater resources. The broad implementation of heat pumps encounters several technological and economic obstacles. High initial expenditures, uncertainty in policy, absence of definitive heat decarbonization strategies, and limited technology adoption are the main barriers. Incentives and subsidies are necessary for further adoption. The integration of solar technology can achieve a higher efficiency. It is a viable solution for areas with sufficient solar radiation. Further research and efforts should be taken in the field to enable them a more attractive option for both residential and industrial applications.

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