Industrial Revolution

Every home that is built is a representation of compromises made between different and often competing goals: comfort, convenience, durability, energy consumption, maintenance, construction costs, appearance, strength, community acceptance, and resale value. Consumers and developers tend to make tradeoffs among these goals with incomplete information which increases risks and slows the process of innovation in the housing industry. The slowing of innovation, in turn, negatively affects productivity, quality, performance, and value. This department features a few promising improvements to the U.S. housing stock, illustrating how advancements in housing technologies can play a vital role in transforming the industry in important ways.

Heat Pumps: An Attractive Choice for Heating and Cooling Needs

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Abstract

Heat pumps continue to be a valuable update to traditional heating and cooling systems in buildings, offering significant advantages in energy efficiency and environmental impact. This versatile technology can provide both heating and cooling from a single system, potentially leading to substantial energy savings and reduced greenhouse gas emissions. Although the initial costs can be higher than conventional HVAC systems, long-term savings and various incentives often offset this investment. Heat pumps come in different types, including air-source and ground-source (geothermal), each with its own benefits and applications. Recent advancements have addressed previous limitations, such as performance in extreme cold, with the development of cold climate heat pumps. The heat pump market continues to experience growth, surpassing gas furnace shipments in the U.S.

The Status Quo

Buildings in the United States use different sources of heating that historically have been based on the country's climate zones. These sources include furnaces and boilers using natural gas, propane, oil, or electricity. Some homes have a device for heating and a separate device for cooling. This scenario has created a variety of heating and cooling methods based on both the historical availability of certain technologies and regional preferences. The energy needed to provide heating and cooling to U.S. households and buildings is a major cost to owning and operating a building, and it is a major contributor to greenhouse gas emissions (BP, 2022; IEA, 2021). Reducing energy consumption will provide benefits in the form of cost savings to Americans while lowering emissions. Enter the world of the heat pump.

Some advantages of heat pumps over the status quo include:

- **Energy Efficiency.** Heat pumps are highly energy-efficient because they transfer heat rather than generate it. This efficiency can lead to significant energy savings compared to traditional heating and cooling systems.
- **Dual Functionality.** Heat pumps can both heat and cool a home, providing year-round climate control from a single system. This functionality can offer more convenience and potentially more cost-effectiveness than maintaining separate heating and cooling systems.
- **Environmental Benefits.** Heat pumps use electricity rather than fossil fuels, reducing greenhouse gas emissions and reliance on oil or gas. Using electricity makes heat pumps a more environmentally friendly option, especially if the electricity comes from renewable sources.

However, some disadvantages of heat pumps exist, including:

- **High Initial Cost.** The upfront cost of purchasing and installing a heat pump can be higher than that of traditional heating and cooling systems. High cost can be a significant barrier for some homeowners, despite potential long-term savings.
- **Performance in Extreme Weather.** Heat pumps can be less effective in cold climates, where their efficiency decreases with the outdoor temperature, and they may require a backup heating source. In such conditions, their operational costs can increase. New cold climate heat pumps (CCHPs) are available that retain high efficiency even when operating in colder climates.
- **Complexity and Maintenance.** Heat pumps are more complex systems compared to traditional HVAC units. As a result, heat pumps can have higher maintenance requirements and potential repair costs. Ensuring proper installation and regular servicing is crucial for optimal performance.

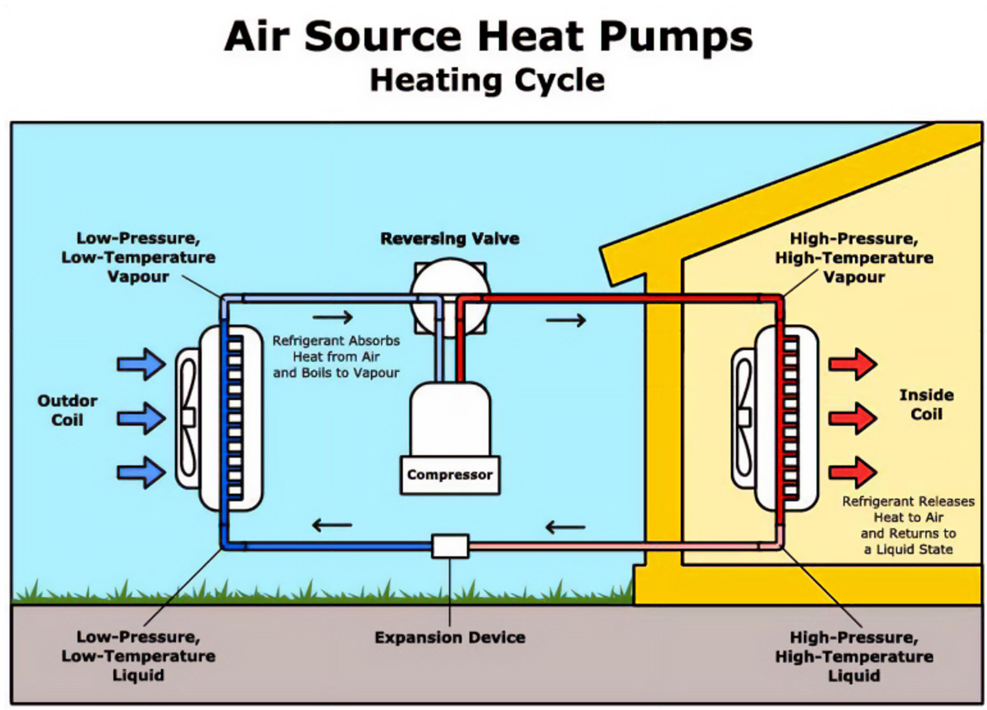
History

Heat pumps have a history dating back to the mid-19th century, when the concept was first theorized by Lord Kelvin in 1852 (Sandfort, 1951). During the 1930s, groundbreaking heat pump research was conducted that resulted in many patents (Kerr, Jr., Stotz, and Stotz, 1934; Neeson, 1938; Brace and Crawford, 1938; Labberton, 1939). Heat pump technology gained more attention and refinement in the following decades, particularly during the energy crises of the 1970s, which spurred interest in more energy-efficient heating and cooling solutions. Since then, advancements in materials, refrigerants, and engineering have significantly improved the efficiency and reliability of heat pumps, making them a popular choice for residential and commercial climate control.

The basic operation of a heat pump relies on the refrigeration cycle and involves four main components: a compressor, an evaporator, a condenser, and an expansion valve (exhibit 1). The compressor circulates refrigerant through the system. In heating mode, the evaporator absorbs heat from the outside. The compressor then pressurizes the refrigerant, raising its temperature. The hot refrigerant moves through the condenser, releasing heat into the indoor space. The expansion valve reduces the refrigerant's pressure, cooling it down. This cycle then repeats. In cooling mode, the process is reversed, with heat being absorbed from indoors and released outside (ASHRAE, 2024).

Exhibit 1

Heat Transfer of an Air Source Heat Pump



Source: U.S. Department of Energy, https://www.energy.gov/energysaver/air-source-heat-pumps

One of the key advantages of heat pump operation is its high efficiency. The efficiency is measured by coefficient of performance (COP), the ratio of heat output to the energy input. Most heat pumps have a COP of at least 3.5, meaning they produce 3.5 kWh of heat for every 1 kWh of electricity consumed, whereas a high-efficiency natural gas furnace might only have a COP of 0.95. Thus, heat pumps can be three to five times more efficient than a high-efficiency gas furnace (ASHRAE, 2024). This high efficiency translates to significant energy savings compared to traditional heating systems. Important to note is that the efficiency of heat pumps can be negatively affected by extreme-cold outdoor temperatures.

Heat Pump Designs for All Needs

Two types of heat pumps exist. *Air-source* heat pumps are the most common type, extracting heat from outdoor air in winter and removing heat from indoor air in summer (exhibit 1). *Ground-source* (geothermal) heat pumps use the constant temperature of the Earth, rather than the outdoor air. Therefore, ground-source heat pumps are more efficient than air-source heat pumps because of the consistent temperature of the ground. However, ground-source heat pumps are initially more expensive to install. Ground-source heat pumps may be installed three ways: vertically, horizontally, or submerged. Vertical installation requires a deep well to be drilled for the piping. Horizontal installation requires a large field where piping can be buried. Submerged installation requires piping to be placed in a nearby body of water as a heat source or sink; however, the vast majority of submerged installations use a system that circulates water through closed loops at relatively shallow depths underground.

Some new applications of heat pump technology have entered the market in recent years. Ductless mini-split heat pumps are appliances (usually hung on walls near the ceilings) that deliver heating/cooling and are ideal for homes without ductwork or for adding temperature control to specific rooms or for additions. Window-mounted heat pumps are like window-mounted air conditioners, but they provide heating as well as cooling. Companies also have introduced heat pumps that can provide hot water for hydronic heating systems. These heat pumps do not fit into all existing systems, but they will for many.

Understanding Heat Pump Ratings

For heat pump systems, two ratings are used: Seasonal Energy Efficiency Ratio (SEER) for cooling efficiency and Heating Seasonal Performance Factor (HSPF) for heating efficiency. SEER measures how efficiently a heat pump can cool a home during warm weather months. The higher the SEER rating, the more energy-efficient the unit is in cooling mode. HSPF, on the other hand, measures the heating efficiency of a heat pump during the cold-weather months. In 2017, the Department of Energy (DOE) announced the adoption of updated rating standards: SEER2 and HSPF2, derived from improved methods of testing and new minimum ratings based on the updated rating standards (DOE, 2017). As of January 1, 2023, heat pumps manufactured must have a minimum SEER2 of 14.3 and a minimum HSPF2 of 7.5 (DOE, 2017). Higher ratings indicate higher efficiency.

When selecting a heat pump, considering both SEER and HSPF ratings is important. In warmer climates, a higher SEER rating is more important, whereas in colder regions, a higher HSPF rating is more beneficial. Specifying heat pumps with an Energy Star label can help simplify product selection. Energy Star-certified heat pumps have a minimum SEER2 of 15.2 and a minimum HSPF2 of 7.8. An Energy Star-certified heat pump intended for cold climates has a minimum HSPF2 of 8.1.

Cost Considerations

The initial cost of an air-source heat pump system for a single-family home can vary widely, ranging from $1,500 to $10,000, with most systems falling between $4,000 and $7,000. Geothermal systems can cost up to $30,000 or more, depending on complexity of the installation of the piping. Although this upfront cost may be higher than traditional HVAC systems, the long-term energy savings often offset the initial investment.

Several factors influence the cost of a heat pump system:

- Type of heat pump (air-source or ground-source).
- Size of home or building.
- Existing ductwork (or lack thereof).
- Local climate.
- Energy efficiency rating of the unit.

In addition to federal incentives, state and local governments and local and regional utilities offer incentives and rebates for installing energy-efficient heat pumps, which can also significantly reduce the upfront costs.

Installation and Maintenance

Proper installation is crucial for optimal heat pump performance. Working with certified HVAC professionals who have experience with heat pump systems is recommended. Some key considerations during installation include correct sizing of the system for the space, proper placement of outdoor units, ensuring adequate insulation and air sealing of the building, and integrating with existing HVAC systems, if necessary.

Heat pumps generally require less maintenance than combustion-based heating systems and have an average lifespan of 15 to 20 years. Regular maintenance tasks include cleaning or replacing air filters, checking refrigerant levels, inspecting electrical connections, and cleaning coils and fans.

A concern for some users is that air delivered by a heat pump does not feel as warm as air delivered by a furnace because heat pumps deliver warm air close to room temperature. Another concern is adopting an automated cycle of heating and cooling the house because changing the temperature significantly via a sudden request can be costly. In such cases, a heat pump may pull upon the assistance of its electric resistance backup to provide supplemental heat, which is inefficient and more costly.

Adoption Rates and Future Developments

Paired with federal and local incentives, heat pumps are the fastest-growing segment of the residential HVAC market. In 2020, heat pump shipments surpassed gas furnaces for the first time. Heat pumps' share in the heating equipment market reached 53 percent in 2022 (IEA, 2023). The heat pump industry is continuously evolving, with ongoing research and development focused on improving efficiency, cold-weather performance, and integration with smart home systems. Some exciting developments include advanced compressor technologies for better cold-weather performance, integration with thermal storage systems for load balancing, hybrid systems combining heat pumps with other renewable technologies, advances in drilling technologies to make geothermal projects less intrusive, and improved control systems for optimized performance and energy management. The increased demand is likely to drive further innovations and cost reductions in the coming years.

The specific developments of CCHPs, advanced heating and cooling systems designed to operate efficiently in regions with harsh winters, are worth noting. These innovative devices have overcome the limitations of traditional heat pumps, which often struggle in subfreezing temperatures. DOE has been actively promoting the development and adoption of CCHPs through initiatives like the Residential Cold Climate Heat Pump Challenge. This program encourages manufacturers to create heat pumps that perform efficiently in cold climates, with the goal of reducing energy consumption and greenhouse gas emissions. Manufacturers have responded, and many models are on the market today. The North American residential CCHP market was $2.7 billion in 2023 and projected to grow 10 percent per year (GMI Research, 2023). Some utilities are developing customer incentives specifically for CCHPs to increase adoption in colder climates.

Conclusion

Heat pumps represent promising technology for efficient, environmentally friendly heating and cooling. Their ability to provide both heating and cooling, high efficiency, and the potential for significant energy savings make them an attractive option for many homeowners and businesses.

Although challenges remain, particularly in terms of cold-weather performance and upfront costs, ongoing technological advancements and increasing support from governments and utilities are addressing these issues. Heat pumps are playing a crucial role in reducing energy costs and greenhouse gas emissions from the building sector.

When considering a heat pump system, carefully evaluating specific needs, the local climate, and available incentives is important. Consulting with experienced HVAC professionals and energy advisors can help ensure choosing the right system for the specific situation and maximizing the benefits of this innovative technology.

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