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Heat Pumps and Their Role in a Clean Energy System

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Overview

Heat pumps are a highly efficient technology for heating residential and commercial buildings. They use electricity to transfer heat from the outside air, or the ground, to the interior, in contrast to more widespread technologies such as warm-air furnaces and variable air volume systems, which typically burn oil or natural gas to heat buildings. Electrification of space heating can help decarbonize the heating sector by using renewable electricity generation from wind, solar, and hydropower. There is no technology that can currently rival heat pumps in efficiently delivering space heating for the residential and commercial sectors [1].

Figure 1: Air-source heat pumps (ASHPs) are now a familiar sight in many residential areas. *Source: Wikipedia Commons.*

Heat pumps are generally classified into two main categories based on the source of heat: air-source heat pumps (ASHPs) and ground-source heat pumps (GSHPs). As the name implies, an ASHP (**Fig. 1)** transfers heat from the cold outdoor air. While this may seem counterintuitive, energy in the form of heat is always present at any temperature above absolute zero. An ASHP simply absorbs some of that heat (thereby imperceptibly cooling the vast reservoir of cold air outside) and transfers the absorbed heat into the interior space. Similarly, ground-source heat pumps extract heat from the ground. They are more expensive but also more efficient than ASHPs due to the nearly constant 40-60°F temperature of the ground throughout the year [2].

> One of the benefits of electric heat pumps is that they can take advantage of the anticipated growth in renewable energy production and provide low-carbon heat generation in the residential and commercial sectors, while also offering potential flexibility on the demand side.

Operating principle

Heat naturally travels from warmer to colder places. In a heat pump, electrical energy is used to move heat in the opposite direction against a temperature gradient. The amount of input energy needed is generally much less than the amount of energy transferred as heat, resulting in the heat pump's high efficiency (see **Efficiency**). Similar to refrigerators and air conditioners, most heat pumps operate on the principle of the vapor-compression cycle, which exploits the physical properties of a volatile evaporating and condensing fluid — a refrigerant — and the heat stored or released during its phase changes. The main components of a heat pump are a compressor, an expansion valve, and two heat exchangers called the evaporator and the condenser (**Fig. 2**) [3]. When refrigerant vapor enters the compressor, it is compressed to high pressure and temperature. The superheated vapor then travels to the condenser, where it condenses into a saturated liquid and gives off heat.

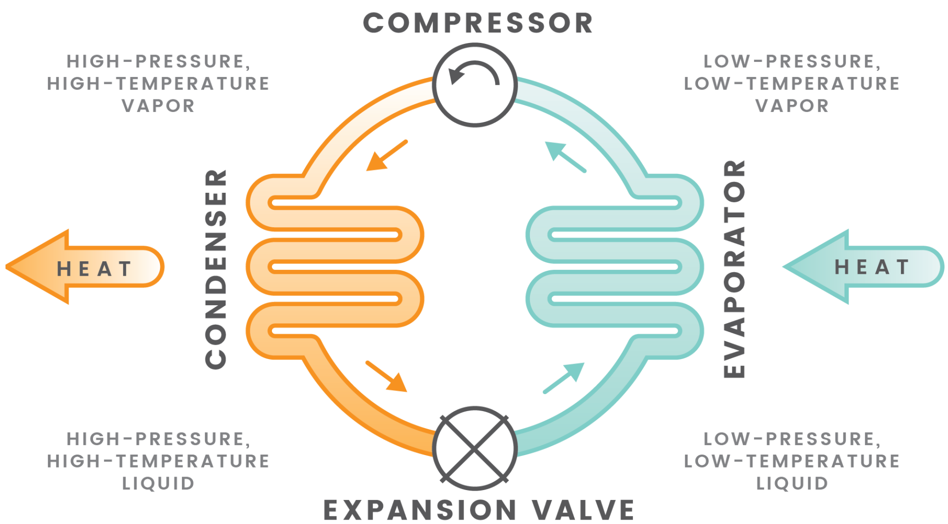


Figure 2: The refrigeration cycle in heating mode. Adapted from [3].

The temperature (and pressure) of the warm fluid is then further lowered when it expands through an expansion valve. The now-cold liquid — colder than the outside air — enters the evaporator, where it absorbs heat from the surrounding outside air (or ground) and boils again to vapor.

In a reversible heat pump, the whole process can be inverted to cool the building by employing a reversing valve. In cooling mode (AC), the outdoor coil becomes the condenser and the lower temperature indoor coil becomes the evaporator.

Cost, payback times, and maintenance

The upfront capital costs for heat pumps are normally higher than for conventional heating systems. In addition, the installation price tag for GSHPs is much greater compared to ASHPs due to the additional labor required for underground piping. Despite the high capital expenditures, heat pumps have passed the break-even point required to save money in the long run due to their high efficiency and minimal operational and maintenance costs [2]. Because electricity tends to be three to four times more expensive than natural gas per unit energy (at current prices), the payback periods for replacing gas for heating buildings can be close to 30 years [2,5]. By contrast, when replacing oil or electrical heating systems, the payback time falls to between 5 and 15 years [2] and can be as low as 3 to 4 years in some geographic locations. Heat pumps require minimal maintenance compared to conventional furnaces as there is no risk of explosion or natural gas leakage.

One disadvantage of ASHPs in cold and damp climates is the freezing of the outdoor heat exchanger during colder spells and the need for defrost cycles. This reduces the efficiency of ASHPs and makes them less suitable than GSHPs for climates with extreme winters [2]. Newer "cold-climate" ASHPs, however, use more efficient compressors and advanced refrigerants that boil at lower temperatures, improvements that make ASHPs economical even in relatively cold climates such as upstate New York (see Case Study).

Role in demand-side management and smart grids

As the share of electricity generation from renewable energy resources increases, the power grid will gradually advance towards a system where electricity demand is continuously adjusted to accommodate variable electricity generation from renewables like wind and solar. Heat pumps are viewed as an enabling technology on the flexible demand side that can be actively managed to support the realization of a smart grid [6]. Well-insulated homes can function as "heat storage" — thermal inertia in buildings allows for time delays in heat production without noticeable loss of comfort. In effect, heat pumps can be used to store electricity as heat at a lower cost than using batteries, while vastly increasing

Efficiency

When measuring the technical performance of heat pumps, it is best to avoid the term "efficiency," which has a very specific thermodynamic meaning. Instead, a commonly used measure is the Coefficient of Performance (COP), defined as the heat delivered Q_{HP} divided by the electrical input energy W_{HP} :

$$\mathrm{COP} = \frac{Q_{\mathrm{HP}}}{W_{\mathrm{HP}}} \tag{1}$$

Because heat pumps move heat as opposed to creating it, the heat energy transferred from the outside can be several times larger than the input electrical energy. A typical ASHP has a COP of 3.2 – 4.5, while a GSHP has a COP in the range of 4.2 – 5.2 [4]. By comparison, an electrical resistance heater can have a maximum COP of only 1 because all the produced heat is created from the input electrical energy. The COP of a heat pump can also be expressed as[1]

$$\mathrm{COP} \approx \eta \frac{T_{\mathrm{hot}}}{T_{\mathrm{hot}} - T_{\mathrm{cold}}} \tag{2}$$

where all losses and deviations from the ideal cycle are represented by η [4]. This shows that the performance of a heat pump is inversely proportional to the temperature difference between the external source of heat (T_{cold}) and the output heat (T_{hot}). To maximize the COP, the difference between inside and outside temperatures (the so-called "lift") needs to be as small as possible. For this reason, heat pumps are more efficient as space heaters than as domestic water heaters (T_{hot} ~90°F for air compared to 130°F for water), and ground-source pumps have higher seasonal efficiency than air-source pumps because ground temperatures fluctuate around an annual average of T_{cold} ~ 50°F, whereas ambient air temperatures in the winter can fall to below T_{cold} = 0°F depending on the geographic location. To account for the seasonal variations in the COP, a seasonally averaged COP (SCOP) is often used, as well as another rating called the Heating Seasonal Performance Factor (HSPF) — a mix of imperial and metric units (Btu/watt-hours). The conversion factor between HSPF and SCOP is 3.412 (HSPF = 3.412 × SCOP). To add to the confusing array of ratings, the Seasonal Energy Efficiency Ratio (SEER), a rating similar to HSPF, is sometimes used in North America specifically for cooling (AC) performance.

[1] Using the Carnot efficiency of a heat engine in reverse.

the potential of demand-side management [2].

At the same time, a key issue is the effect of heat pumps on peak electricity demand in areas with cold winters. In such climates, electricity demand tends to peak in the coldest months and the use of heat pumps can exacerbate this effect [1]. Solar energy production is correlated with air temperature and therefore anti-correlated with space heating demand, which adds to the challenge. Development of scalable smart controls for large numbers of heat pumps and expansion of the grid to interconnect broad geographic areas can help alleviate these problems.

Carbon emissions

CO_2 emissions from heat pumps are necessarily linked to the carbon intensity of the electricity they use. Thus, the marginal carbon intensity of the grid at a given point in time and a given location can greatly influence the attractiveness of heat pumps as a decarbonization option for the heating sector. Studies have shown that CO_2 emissions from domestic heating are reduced by approximately 50% on average when heat pumps displace solid fuel, oil, or electric heating, and by 10% to 35% when they displace natural gas heating [2,7,8]. One concern regarding the carbon footprint of heat pumps is their use of refrigerants with very high global warming potential (GWP) — about 2,000 times that of CO_2. While there is no impact on climate during heat pump operation, refrigerant leakage is a serious concern and needs to be minimized over the life span of the heat pump [9].

Case Study: New York State

The 2030 target for greenhouse gas (GHG) emissions reductions in New York State is 40% below 1990 levels. In order to reach this goal, it is essential to achieve substantial reductions in the use of fossil fuels in the residential heating sector. Space heating is the largest single residential energy end-use in New York State, accounting for 56% of the residential energy consumption [10]. Space conditioning and water heating account for more CO_2 emissions than the entire electricity sector of New York State combined (including electricity imports). The residential sector itself is responsible for over 60% of the emissions associated with space conditioning and water heating and the vast majority of those emissions come from residential space heating [11].

Using heat pumps to displace fossil fuel heating systems is the most promising path towards reducing GHG emissions in the residential heating sector (in addition to the weatherization of homes). Electrification also makes space heating renewable-grid ready, meaning that emissions reductions will continue to improve automatically as the proportion of renewables increases towards New York State's target of 50% renewables by 2030.

Table 1 summarizes the estimated installation costs, annual energy use, annual energy costs, cumulative CO_2 emissions over 15 years, and payback times for cold-climate ASHPs and GSHPs compared to natural gas and oil heating systems. Natural gas and heating oil are by far the most common heating fuels in New York State, accounting for 57% and 29% of all residential heating systems respectively [10]. The residential buildings considered here are single unit structures with 1,500 to 2,000 square feet of heating area, assuming the retrofit takes place at a time when the oil or natural gas furnace needs replacement or, equivalently, during new construction.

These estimates do not include discount rates or projections of future fuel costs due to the high

	Installation cost[2] ($)	Annual energy use[3] (MMBtu)	Annual energy cost[4] ($)	CO_2 emissions, 15 years[5] (metric tons)	Payback time vs Oil (years)	Payback time vs NG (years)
ASHP	$8,300	26	$1,295	19.5	3.9	23.2
GSHP	$24,000	20	$996	15.0	14.3	41.3
Oil	$4,000	100	$2,392	109.7	-	-
Natural Gas	$4,000	100	$1,481	79.6	-	-

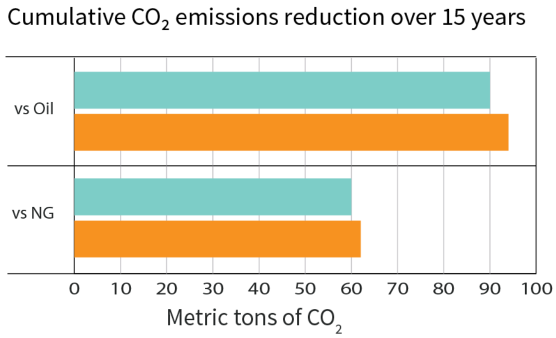
Table 1: Costs, CO_2 emissions and payback times for different heating options in New York State

[2] Source: IEER [11]

[3] Assuming an average annual thermal requirement of 90 MMBtu for Upstate New York [11,12], 90% efficiency for oil and gas heating systems, and average COP values of 3.5 and 4.5 for air-source and ground-source heat pumps respectively. MMBtu means million Btu. 1 kWh (electrical) = 3,412 Btu.

[4] Energy costs per MMBtu in New York State: electricity = $49.82 [11]; natural gas = $14.81, heating oil = $23.92 (NYSERDA). Natural gas and heating oil prices are averaged over 10 years to account for high price volatility.

[5] CO_2 emissions coefficients (kg CO_2/MMBtu) for fossil fuels: natural gas = 53.07, oil = 73.16 (EIA). The average CO_2 emissions of electricity in New York State for the period 2015 – 2030 are estimated to be 0.171 kg CO_2/kWh [11]



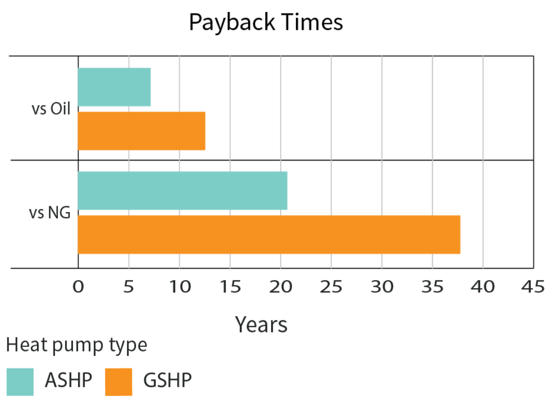


Figure 3: Estimated CO_2 emissions reduction and payback times for ASHPs and GSHPs.

uncertainty in natural gas and oil prices. The societal benefits of reducing carbon emissions, the health benefits of reducing air pollution, and the climate impacts of upstream methane emissions associated with natural gas production and distribution are also not considered in this simple analysis.

Table 1 and **Fig. 3** above suggest that switching from fossil fuel heating to either an ASHP or a GSHP system can result in significant CO_2 emissions reduction over 15 years. The two heat pump options have a comparable emissions reduction potential with a slight advantage for GSHPs. The numbers also suggest that it is very cost-effective to replace an oil furnace with a heat pump system, although the break-even times are quite different for the two heat pump options: ~ 4 years for an ASHP and slightly over 14 years for a GSHP. The lower installation cost of the former leads to significantly higher net benefits over 15 years. When it comes to replacing natural gas heating systems, however, the economics are quite different — the simple payback times become 23 and 41 years respectively for the two heat pump options. With a life span of 15 to 20 years, an ASHP can nearly break even and a GSHP with a life span of 25 to 30 years would be unable to do so. It is important to keep in mind that these estimates can vary substantially depending on the geographic location, the heat pump size, and, most importantly, the fuel and electricity prices. In general, the current low prices of natural gas compared to electricity coupled with the greater upfront costs make ASHPs marginally economical and GSHPs uneconomical as a natural gas heating replacement unless the co-benefits of CO_2 emissions and air pollution reduction are taken into account. An additional benefit of heat pumps is that they can serve as a hedge for volatile fossil fuel prices due to their lower energy consumption and the relatively stable cost of electricity.

We note that the New York City area is expected to be slightly less cost-effective for heat pump adoption compared to Upstate New York due to the lower heating requirements for apartment buildings, the lower cost of natural gas and heating oil, the higher equipment and labor costs, and the higher electricity prices [13]. These higher costs are somewhat offset by the milder climate in the New York City area, which improves the seasonal efficiency of air-source heat pumps.

The estimates above suggest that a switch from fossil fuel space heating to efficient electrical heat pump systems — specifically ASHPs — should be encouraged in New York and the state should prioritize policies to overcome the various market barriers for heat pump adoption (high upfront costs, split incentives, cold climate concerns, lack of information). In particular, the state should facilitate the rapid retrofitting of all oil-heated homes with efficient electrical systems. In areas without natural gas infrastructure, New York State residents can affordably switch directly to efficient heat pump systems. In areas with natural gas infrastructure, ASHPs may still be the most beneficial option for new buildings, especially when CO_2 emissions, air pollution, and the volatility of fossil fuel prices are taken into account. Meeting the goal of

40% reduction in CO_2 emissions from the residential heating sector in New York State by 2030 would require replacing all existing oil furnaces and over 20% of existing natural gas furnaces with efficient heat pumps by 2030, assuming the state's target of 50% renewable energy by 2030 is also met.

In summary: Heat pumps have the potential to effectively replace fossil fuel heating systems, decarbonize the heating sector, and lower heating costs over conventional heating systems. Some challenges remain, including high initial capital costs and added grid complexities in colder climates. To overcome market and behavioral barriers for heat pump adoption — such as upfront cost, low priority for energy efficiency in decision-making, principal-agent problems, etc. — policies involving financial incentives, utility programs, minimum energy performance standards, and roadmaps for market expansion need to be adopted. [14]

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