Sponsored content: The evolution of heat pump technology

A knowledge of where heat pumps have come from will help engineers understand when and how to implement them

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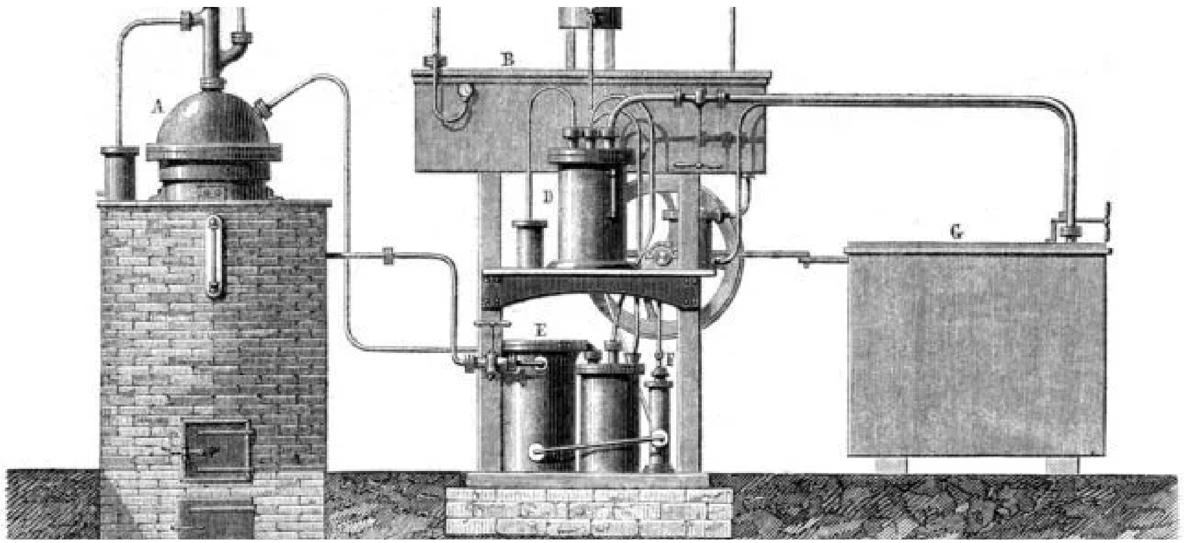

Figure 1: Ferdinand Carré's ice-making absorption heat pump was one of the first innovations in heat pump technology. Courtesy: Daikin Applied

The early pioneers of heat pump technology could not have anticipated the incredible potential for their novel inventions in light of current climate change challenges. In the 1850s, French brothers Edmond and Ferdinand Carré developed the first absorption cooling heat pumps to make ice in Paris and Peter Von Rittinger, an Austrian engineer, developed the first vapor compression heat pump to produce salt from brine.

Now, as the desire for more sustainable buildings grows, the need for decarbonized heating and cooling solutions is becoming increasingly urgent. Enter heat pumps — electricity-powered technology reshaping the way buildings are heated and cooled. The concept of a heat pump is based on the principle of transferring heat from one location to another using a refrigerant. In essence, it's the reverse of how conventional air conditioning technology operates today.

In North America, heat pumps are most commonly used in residential applications. In commercial spaces where natural gas was and continues to be readily available and inexpensive, the economics of heat pumps have not been as compelling. However, as the need for energy-efficient and carbon-free heating and cooling solutions has grown, heat pumps have gained interest for commercial buildings as well. Combined with other levers for decarbonizing heating, ventilation and air conditioning (HVAC) systems, such as improving efficiency or choosing more sustainable refrigerants, electrification via heat pumps is enabling building designers and operators to realize their decarbonization goals.

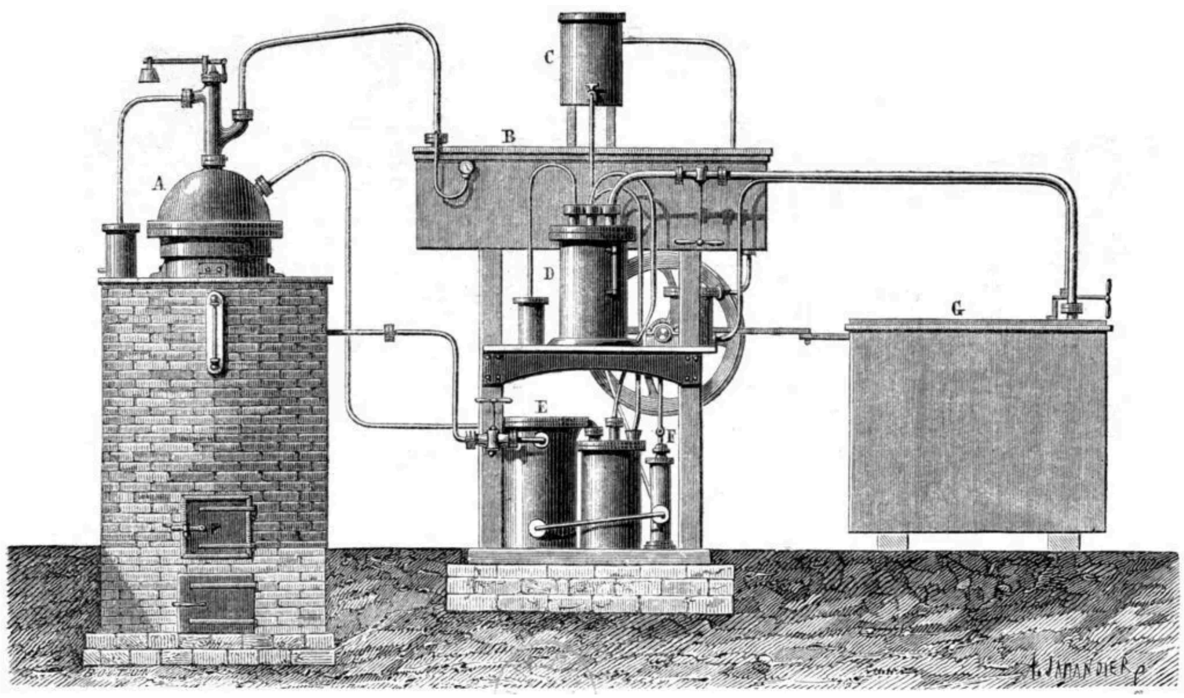

Figure 1: Ferdinand Carré's ice-making absorption heat pump was one of the first innovations in heat pump technology. Courtesy: Daikin Applied

Closing the heat pump gaps

A conventionally held belief is that heat pumps don't work well in cold climates — that they struggle to keep buildings comfortable and don't run efficiently when temperatures drop. However, newer technologies are helping heat pumps overcome this perception.

One historic and prominent challenge for heat pumps was that as outdoor temperatures plummet, so does the heating capacity of the unit, so the least amount of heat is given when it is most needed. Inverter compressors, which can vary their speed, have traditionally been used to reduce capacity during times of low load. But now inverters are being used to do the opposite — to boost the compressor capacity during cold conditions, helping minimize capacity reduction and deliver ample heat. Inverters also improve the overall efficiency of the unit, which has an added benefit of further reducing carbon emissions.

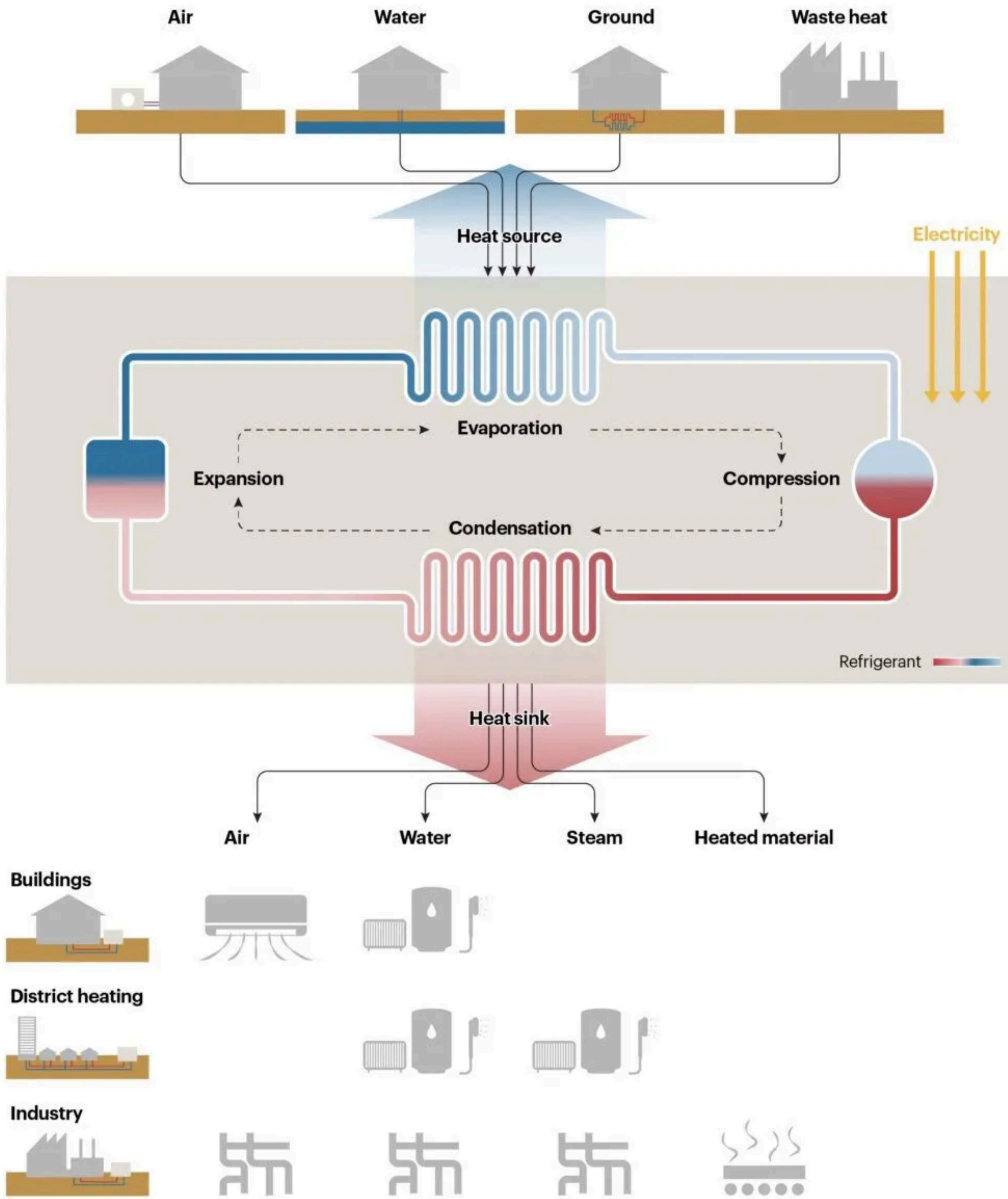

Figure 2: This diagram explains the heat pump at a conceptual level. Courtesy: IEA (2022), The Future of Heat Pumps, IEA, Paris https://www.iea.org/reports/the-future-of-heat-pumps, Licence: CC BY 4.0

Another potential issue surfaces when considering indirect emissions and looking at the entire building and utility ecosystem. The transition from gas to electricity shifts carbon emissions to the electric grid and, depending on how much electricity is generated by fossil fuels versus renewable sources, this can have a significant impact on the overall environmental benefit. Every power grid has a 'grid emissions factor' that quantifies how much carbon dioxide (CO2) is created per kilowatt-hour (kWh) of electricity generated. The lower the carbon intensity per kWh, the less indirect emissions are tied to an electrified HVAC system. This concept also extends to the emissions from gas heating compared to the overall emissions at the building and grid level combined. Below a certain efficiency, CO2 emissions can be higher with a heat pump than gas, depending on the grid emissions factor.

Figure 3 shows an example of this effect. It approximates the emissions for both natural gas and electricity for a non-specific electrical grid in the U.S., assuming an emissions factor of 387 grams per kWh. CO2 emissions of heating with natural gas and electric resistance are plotted in orange and gray, respectively. Comparing the two, electric resistance heat has higher CO2 emissions than direct natural gas heating due to the fossil fuels required to generate the electricity.

Figure 3: An approximation of the emissions for natural gas and electricity for a non-specific electrical grid in the U.S. Courtesy: Daikin Applied

Heat pump emissions, in comparison, are added in blue and vary as the efficiency of the heat pump varies. In conditions where the heat pump can run with a higher coefficient of performance (COP), the emissions can be less than natural gas. As the outdoor ambient temperature drops and the COP of the heat pump falls below ~1.8, the emissions increase above natural gas. Of course, the actual value will fluctuate depending on the specific electrical grid and its generation source.

Potential trade-offs will continue to evolve with changes in the electric and gas utility industry and rate structures, and with parallel advancements in heat pump efficiency and applicability. For example, inverter compressors can help mitigate this emissions-focused challenge. By increasing the overall efficiency of the heat pump and improving low-ambient performance, inverters improve the useful capacity range and average efficiency of the unit, making it more advantageous for a given set of outdoor temperature conditions from an emissions perspective.

A dual-fuel approach

Considering the above, there are situations where combining a heat pump and gas heating provides the best of both worlds. Even in colder climates, the vast majority of operating hours occur during milder ambient temperatures, where leveraging heat pumps reduces carbon emissions from fossil fuels.

Then, during the coldest weather when the heat pump is at its lowest capacity and efficiency, the HVAC system switches over to gas heating. This could be a win/win for multiple design goals. It avoids oversizing the heat pump to cover the worst-case conditions, which reduces the cost of the heat pump equipment. Additionally, gas heating equipment is typically less expensive on a thousand British thermal units per hour basis. It also gives the system a backup heat source for increased redundancy that is not sensitive to extremely low outdoor temperatures. Finally, compared to heat pumps that use electrical supplemental heat, it reduces the peak electrical draw from the heat pump equipment on the coldest days when electrical grids see high demand.

Combination heat pump and natural gas heating systems are analogous to hybrid cars. Hybrid cars provide a technology bridge to address the range and charging availability concerns of electric vehicles. Similarly, heat pumps with secondary gas heating for cold temperatures address capacity, efficiency and performance concerns of present-day heat pumps alone.

Figure 4: A demonstration of the operating envelope for a heat pump. Courtesy: Daikin Applied

For owners seeking 100% electrification of their building, this is not an option. However, for those who want to balance climate benefits and the relative impact of each dollar spent, it's an approach to consider. In most cases, decarbonization is a multi-leg journey not a direct destination. Taking steps today, even moderate ones, moves organizations closer to their goals. It's also worth mentioning that in areas where the grid is powered by a higher percentage of renewable energy, dual-fuel systems may not present a favorable emissions case. This will be increasingly true as renewables become a greater part of the generation mix for more electrical grids.

The economics of heat pumps

Another commonly cited concern is that heat pumps can't compete with gas heating from an economic standpoint. Heat pumps often carry a first-cost premium compared with gas heating, and the payback can be difficult to demonstrate using traditional cost measures in areas with 'typical' gas and electricity rates. However, numerous cities are putting building performance standards in place for commercial facilities that will financially penalize owners who have buildings that use too much energy or emit too much carbon pollution. These additional financial motivators are causing building owners to re-think the cost/value of a heat pump solution.

The cost to decarbonize and electrify can vary depending on the type of HVAC equipment, and whether a facility is being retrofitted or raised from the ground up. It's easiest to create a favorable business case for new construction projects since architects and engineers can design the building, and specify and size HVAC systems with decarbonization in mind from the outset. It is slightly more difficult in a building retrofit with rooftop units. Though not without some added cost, changing from a gas rooftop to a heat-pump rooftop unit is often feasible with the main changes being a new adaptor roof curb and larger-size electrical feed (when backup electric resistance heat is used).

Some new heat pump rooftop units are being designed with smart electrical sizing that will match up well with traditional gas rooftop units, and only requires one additional electrical feed for the difference to cover the electric heat, rather than requiring that the entire electrical feed be removed and upsized.

Replacing gas boilers for high-temperature hydronic systems with heat pumps is more difficult. These high-temperature systems strain heat pumps, lowering their efficiency and minimum ambient operating temperature. Lowering the water temperature increases unit efficiency and lowers grid emissions, but can be costly because the existing heating coils and piping may not be sized correctly. However, if the goal is environmental benefit and CO2 reduction, designers should take a hard look at reducing the hot water temperature.

As mentioned, when the impact of electrical grid emissions is accounted for, operating heat pumps in conditions that result in low COPs will reduce the total carbon-reduction benefit. Milder-temperature systems can both increase efficiency and extend their operation to lower ambient temperatures.

To explain how hot water temperature impacts the low ambient operation of a heat pump, consider the example operating envelope below. As long as the ambient and hot water conditions fall within the box, the heat pump is able to operate. In this example, to achieve 140°F hot water, ambient temperatures need to be 50°F or higher. But if the hot water temperature is reduced to 120°F, the heat pump can operate down to below 0°F ambient temperature — a huge improvement. This is why the system design is key; it enables heat pumps to leverage their strengths and minimize their current weaknesses.

The future of heat pumps

Heat pumps, in all of their form factors and energy exchange configurations, will play a pivotal role in the decarbonization of buildings. In the residential market, heat pump sales exceeded gas furnace sales in 2022, and growth is anticipated in commercial and institutional buildings as well. Expect to see creative technical innovations in heat pumps and HVAC systems on the horizon as manufacturers and system designers figure out new ways to adapt to the need to reduce emissions. More efficient equipment and system solutions, along with refrigerant innovations, are just a few of the ways HVAC systems will evolve. The runway is long for innovation of heat pump technology, and the application of heat pump systems in new and existing buildings.

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