Engineering 29 (2023) 2–4

Contents lists available at ScienceDirect

Engineering

journal homepage: www.elsevier.com/locate/eng

News & Highlights

As Planet Warms, Heat Pumps Get Hotter

Chris Palmer

Senior Technology Writer

The heat pump, an old device dating back to the early 1850s [1], has captured new attention for its potential to help meet climate change goals. Driven in large part by legislated incentives and bans on fossil-fuel heating in a growing number of countries, the heightened interest has also spawned improvements in the technology's efficiency and cost. Another unique benefit is for one device to provide, depending on seasonal needs, both heating and cooling.

"The heat pump is the easiest, most straightforward way to stop using fossil fuels in buildings," said Parth Vaishnav, assistant professor of sustainable systems at the University of Michigan in Ann Arbor, MI, USA. "It is one of those rare situations where a mature technology can decrease the use of fossil fuels right now."

Most buildings rely on burning natural gas or heating oil for heating, which now accounts for an estimated 10% of total global greenhouse gas (GHG) emissions [1]. The most common type of heat pumps, called air-source heat pumps, have the potential to reduce GHG emissions by at least 50% compared to gas furnaces, according to a recent study that includes an accounting for the possible contribution of leaking refrigerants [2]. While CO_2 emissions are avoided, some GHG potential remains. This is because, although the leakage is generally small, the refrigerants used in most heat pumps today are very potent GHG. Finding refrigerants with reduced GHG potential remains an area of active research.

Although heat pumps have been around for decades, they only fulfilled 7% of global heating demand in 2022 [3]. That percentage approaches 10% in the United States [4], which experienced a major milestone in 2022 when the sale of several millions of heat pumps surpassed those of gas furnaces by about 400 000 units [5]. In 2022, the median price to buy and install a ducted, air-source heat pump in the United States was 7791 USD, compared to 6870 USD for a gas furnace [6]. However, a heat pump becomes even more cost-competitive if it replaces both a gas furnace and central air conditioning (AC) or is built into a new structure. "In existing homes, it rarely makes sense to rip out a perfectly good system and replace it with heat pumps," Vaishnav said. "What tends to make more sense is if your AC goes or your furnace goes, then you might want to consider replacing it with a heat pump."

To encourage consumers to choose heat pumps, the Inflation Reduction Act passed by the US Congress in 2022 includes federal tax credits of up to 2000 USD to any homeowner who installs a heat pump [7]. The legislation additionally created a rebate program that covers 100% of the cost—up to 8000 USD—of heat pump purchase and installation for low-income households; median-income households are eligible to receive a rebate of 50% of the cost [7]. Also in 2022, the US President invoked the Defense Production Act to boost domestic manufacturing of heat pumps [8] and the US senators introduced two bills that aim to promote and accelerate heat pump adoption [9]. Globally, many countries are similarly offering incentives for the purchase and installation of heat pumps [10]; this includes at least 20 countries in the European Union [11], where heat pumps have become a critical part of efforts to pivot away from dependence on fossil fuels [12].

Heat pump sales are also being driven by emerging bans on gas-powered heating appliances, like furnaces and water heaters, in newly constructed homes. Such bans have been enacted in American cities including New York City [13] and Berkeley [14] and San Francisco [15] in California. Similar bans will take effect country-wide in Germany in 2024 and the Netherlands in 2026 [16].

Even in freezing cold weather, heat pumps can be more energy efficient than gas or oil furnaces. Many models still operate close to normal in ambient temperatures of around −24 °C [17], though they tend to carry hefty price tags ranging from 8700 to 32 000 USD [18]. In the US state of Maine, where heat pump adoption is growing but most homes still burn oil, homeowners making the switch can save thousands of dollars in annual energy bills [4]. And several cold-weather countries, including Norway, Sweden, and Finland, are increasingly embracing heat pumps, with at least 40% of buildings in those countries using the technology [19]. "In Scandinavia, there is widespread adoption of heat pumps partly because electricity is cheaper in those places than gas," Vaishnav said.

The concept behind heat pumps is relatively simple: powered by electricity, these all-in-one heating and cooling units are essentially air conditioners that run in two directions. Their burgeoning use in homes and commercial buildings was prompted by reduced prices for electricity in the 1960s and the oil embargo in the 1970s; they are now used as heat sources for water heaters, clothes dryers, and even beer breweries [20]. "People see this transition to electric heat pumps as this impossible task when, in fact, there are heat pump vapor-compression cycles being used everywhere around us," said Stephen Pantano, the head of market transformation at Rewiring America, a Washington, DC, USA-based nonprofit

E-mail address: dave.egerter@gmail.com

https://doi.org/10.1016/j.eng.2023.08.004

promoting electrification (the conversion of machines and systems to electric power).

In general, heat pumps work by capturing heat from one place and moving it elsewhere. In the winter, they draw heat indoors and dump cold air outdoors. In the summer, they push hot air out and bring cooled air in. The critical component of a heat pump is the refrigerant, the material that moves in a circuit throughout the device, absorbing and then releasing heat as it travels. Heat pump refrigerants have very low boiling points, typically below −25 °C. When it begins its journey through a heat pump, the refrigerant is around that temperature and in liquid form. Initially, the refrigerant, pumped by electricity, flows through a heat exchanger, past outside air (for an air-source heat pump), and warms up enough to start boiling, changing from a liquid to a gas. It then moves through a compressor, which squeezes the gaseous refrigerant into a smaller volume, increasing its pressure. Along the way, the refrigerant warms, so by the time it moves past the compressor, it is warmer than the indoor environment.

The next leg of the trip takes the refrigerant through another heat exchanger. By this point, it is a warm gas, typically above 37 °C, flowing into a relatively colder room. As a fan helps transfer its heat into the house, the refrigerant returns to its liquid phase. In the final stage of its loop, the refrigerant travels through an expansion valve, releasing its pressure, and cooling it back down to be ready to absorb more heat from outside [1]. For cooling, the process works in reverse.

Even when it is frigidly cold outside, some heat is still available for capture (as long as the air temperature is above the refrigerant's boiling point), although air-source heat pumps must work harder to extract that heat as the outside temperature drops. Ground-source and water-source heat pumps, in which the heat exchanger coils are buried underground or run through a pond or near-by other body of water, do not face this challenge and are generally more efficient; for these heat pumps, while the temperature of the heat source is more stable, they are generally much more expensive to install.

Refrigerants, which may leak over the life of the heat pump, during its manufacture, and during disposal, are one major area of improvement in the technology. Freon, a common chlorofluorocarbon (CFC) also called R-22, used to dominate the market, but has been phased out globally due to its ozone-depleting effects; CFCs are also potent GHGs, with as much as a 10 000-times greater potential for warming than CO_2 [21]. "We have moved away, quite appropriately, from CFCs after the Montreal Protocol, though many of the new refrigerants still have substantial global warming potential," Pantano said. "There is a big push now to bring other refrigerants with zero- or low-global-warming potential to market."

Today, a chemical mixture called R-410A is one of the most widely used heat pump refrigerants. In addition to being slightly less harmful to the ozone layer than R-22, R-410A has a lower boiling point than R-22 (at 1 atm, 1 atm = 101 325 Pa; −48.5 vs −40.8 °C), meaning it can absorb more heat at lower temperatures, boosting efficiency in the cold [22]. With the phasing out of R-410A to begin in the United States in 2025 [23], companies have been developing and testing next-generation refrigerants such as R-32 and R-466A [24,25]. Compared to R-410A, for example, R-466A has a slightly lower boiling point and a 65% lower impact on global warming [24,25]. Some heat pumps now on the market use supercritical CO_2 as the refrigerant; its global warming potential is 65 times lower than that of R-32 and 2000 times less than that of R-410A [26].

Other components have improved as well. Modern compressors push refrigerants to higher pressures using less power than previous versions, and new variable-speed compressors allow power to be ramped up and down for greater efficiency. Advances in heat exchanger design have also increased heat pump efficiency [27]. Other innovations include more reliable sensors and coatings within compressors that reduce ice formation [28].

Heat pump installation can be quite straightforward. Connecting ducted heat pumps to existing forced-air systems can minimize installation costs; because installing a heat pump is like setting up central AC, most homes with such systems already have the necessary electrical connections and lines for the wiring and the refrigerant. Ductless air-source heat pumps are also easy to install. The outdoor portion is identical to that of ducted models (Fig. 1), but rather than hooking up to a central forced-air system, the condenser connects via refrigerant lines snaked through small holes in the walls to one or more "heads," essentially wall-mounted heat exchangers with fans to vent the heated or cooled air indoors.

Like standard, window-mounted air conditioners, new saddle-shaped units can be installed in as little as 15 minutes on most windowsills, although the price of these units (without incentives)

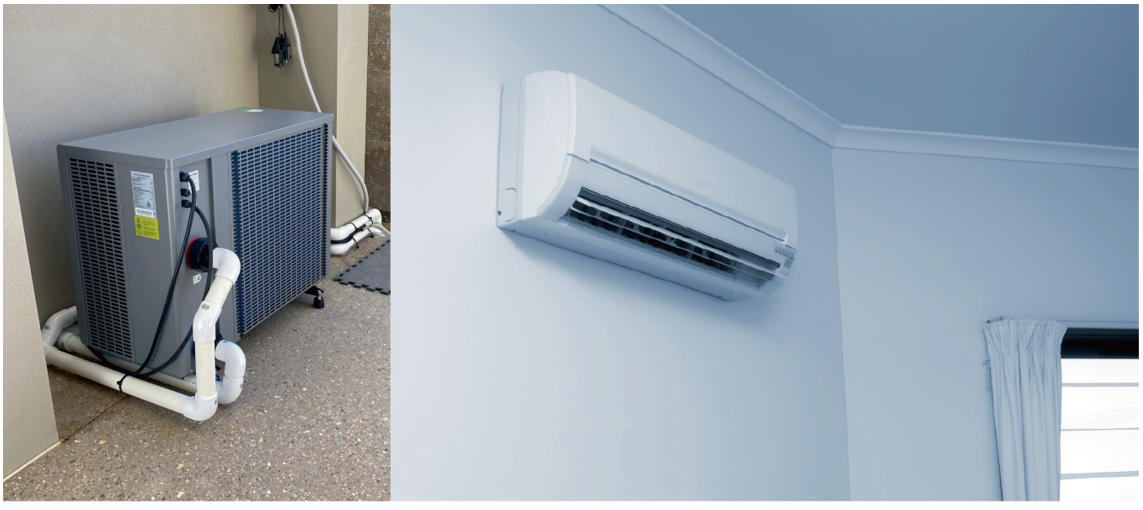

Fig. 1. While (a) the outdoor component of air-source ducted and unducted heat pumps are the same, ducted systems connect to existing components of previously installed forced air and central AC systems. Easy-to-install, unducted heat pumps are modular and connect to (b) wall or ceiling mounted blowers. Credit: both, public domain.

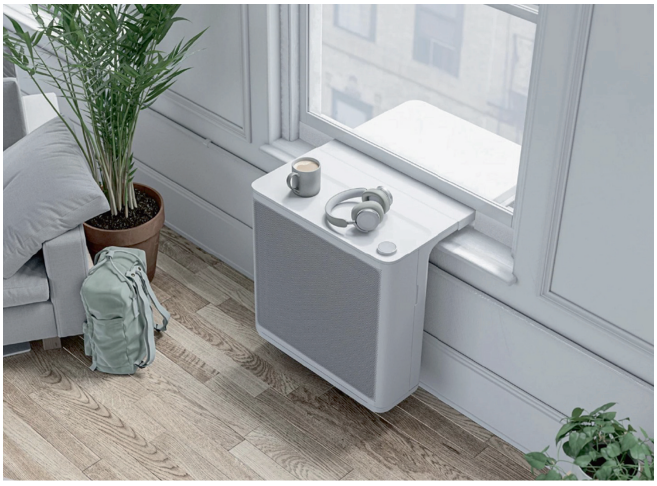

Fig. 2. Gradient's saddle-shaped windowsill heat pump, first commercially available in 2023, does not block the view and installs in as little as 15 minutes. Without incentives and/or rebates, the unit costs 4997 USD. Credit: Gradient (public domain).

is almost ten times higher (Fig. 2). These units are now being sold by several companies, and the state of New York recently agreed to pay 70 million US dollars to two US-based companies—Gradient (San Francisco, CA) and Midea America (Parsipanny, NJ)—to produce 30 000 units for New York City public housing [29].

The ease of installation makes windowsill units attractive to those looking to cut installation costs and to renters, who can take their purchases with them when they leave. "If you are renting in a building with steam heat, it is very difficult to electrify that building, and, if you are the renter, you do not have agency over that decision anyway," Pantano said. "Or, if you are in an older home in the northeast United States and you have expensive electric baseboard or oil heating and want to add a heat pump to a room, a saddle-style heat pump keeps your window space free."

Because they are modular, the ductless and windowsill units can be sized or combined to generate as much heat—and cooling—as needed, although installing multiple such units quickly becomes expensive. Further cost reductions and many more technical solutions are needed to make heat pumps as widely adopted as envisioned, Pantano said. "This is tried-and-true technology, but every home is unique, and the built environment is a big jigsaw puzzle of different stuff everywhere."

References

[1] Crownhart C. Everything you need to know about the wild world of heat pumps [Internet]. Cambridge: MIT Tech Review; 2023 Feb 14 [cited 2023 Jun 30]. Available from: https://www.technologyreview.com/2023/02/14/1068582/everything-you-need-to-know-about-heat-pumps/.

[2] Pistochini T, Dichter M, Chakraborty S, Dichter N, Aboud A. Greenhouse gas emission forecasts for electrification of space heating in residential homes in the US. Energy Policy 2022;163:112813.

[3] Delmastro C, Briens F, Martinez-Gordon R, Husek M. Heat pumps [Internet]. Paris: International Energy Agency; 2022 Sep 1 [cited 2023 Jun 30]. Available from: https://www.iea.org/reports/heat-pumps.

[4] Lawrence C, Berry C. U.S. households' heating equipment choices are diverse and vary by climate region [Internet]. Washington, DC: Energy Information Administration; 2017 Apr 6 [cited 2023 Jun 30]. Available from: https://www.eia.gov/todayinenergy/detail.php?id=30672.

[5] Shao E. As heat pumps go mainstream, a big question: can they handle real cold? [Internet]. New York City: The New York Times; 2023 Feb 22 [cited 2023 Jun 30]. Available from: https://www.nytimes.com/interactive/2023/02/22/climate/heat-pumps-extreme-cold.html.

[6] Consumer Reports (CR). Heat pump buying guide [Internet]. Yonkers: Consumer Reports; 2022 May 26 [cited 2023 Jun 30]. Available from: https://www.consumerreports.org/appliances/heat-pumps/buying-guide/.

[7] Calma J. This act is the biggest step against climate change the US has ever taken [Internet]. New York City: The Verge; 2022 Aug 8 [cited 2023 Jun 30]. Available from: https://www.theverge.com/2022/8/8/23296657/inflation-reduction-act-us-global-climate-change-goals-senate-passes-bill.

[8] Calma J. President Joe Biden will pause solar tariffs and invoke Defense Production Act for clean energy [Internet]. New York City: The Verge; 2022 Jun 6 [cited 2023 Jun 30]. Available from: https://www.theverge.com/2022/6/6/23156326/biden-solar-tariffs-renewable-energy-commerce-investigation.

[9] Urbanek L, Walls S. New senate bills encourage U.S. heat pump manufacturing jobs [Internet]. New York City: National Resource Defense Council; 2022 May 24 [cited 2023 Jun 30]. Available from: https://www.nrdc.org/bio/lauren-urbanek/new-senate-bills-encourage-us-heat-pump-manufacturing-jobs.

[10] Crownhart C. The surprising truth about which homes have heat pumps [Internet]. Cambridge: MIT Tech Review; 2023 Jun 14 [cited 2023 Jun 30]. Available from: https://www.technologyreview.com/2023/06/14/1074652/residential-heat-pumps-cost/.

[11] Santos B. Residential heat pump subsidies across Europe [Internet]. Berlin: PV Magazine; 2023 Mar 22 [cited 2023 Jun 30]. Available from: https://www.pv-magazine.com/2023/03/22/residential-heat-pump-subsidies-across-europe/.

[12] Gilbert A, Bazilian MD, Gross S. The emerging global natural gas market and the energy crisis of 2021–2022 [Internet]. Washington, DC: Brookings Institution; 2021 Dec 1 [cited 2023 Jun 30]. Available from: https://www.brookings.edu/research/the-emerging-global-natural-gas-market-and-the-energy-crisis-of-2021-2022/.

[13] Calma J. New York becomes largest US city to ban new gas hookups [Internet]. New York City: The Verge; 2021 Dec 15 [cited 2023 Jun 30]. Available from: https://www.theverge.com/2021/12/15/22837799/new-york-city-bans-gas-hookups-new-buildings.

[14] Berkeley becomes first U.S. city to ban natural gas connections in new buildings [Internet]. Berkeley: Bay Area Regional Collaborative; 2019 Jul 17 [cited 2023 Jun 30]. Available from: https://barc.ca.gov/whats-happening/news/berkeley-becomes-first-us-city-ban-natural-gas-connections-new-buildings.

[15] Chilukuri S. Broken furnace? In the Bay Area, soon you'll have to replace it with a heat pump [Internet]. Seattle: Grist; 2023 Mar 20 [cited 2023 Jun 30]. Available from: https://grist.org/buildings/bay-area-ban-sales-gas-powered-furnaces-heaters/.

[16] Marcacci S. The World's three largest economies go all-in on heat pumps: how policy can cut gas use and energy bills [Internet]. New York City: Forbes; 2022 Nov 15 [cited 2023 Jun 30]. Available from: https://www.forbes.com/sites/energyinnovation/2022/11/15/the-worlds-three-largest-economies-go-all-in-on-heat-pumps-how-policy-can-cut-gas-use-and-energy-bills.

[17] Schoenbauer B. Cold climate air source heat pump final report [Internet]. Minneapolis: Center for Energy and Environment; 2017 Nov 1 [cited 2023 Jun 30]. Available from: https://www.mncee.org/cold-climate-air-source-heat-pump-final-report.

[18] McCabe L. 4 reasons you might consider a heat pump (plus a few caveats) [Internet]. Yonkers: Consumer Reports; 2022 Jul 19 [cited 2023 Jun 30]. Available from: https://www.consumerreports.org/appliances/heat-pumps/reasons-to-consider-a-heat-pump-for-your-home-a6507162057/.

[19] Rosenow J, Gibb D, Nowak T, Lowes R. Heating up the global heat pump market. Nat Energy 2022;7(10):901–4.

[20] Temple J. How electrifying steam could cut beer's carbon emissions [Internet]. Cambridge: MIT Tech Review; 2023 Jun 27 [cited 2023 Jun 30]. Available from: https://www.technologyreview.com/2023/06/27/1075548/how-electrifying-steam-could-cut-beers-carbon-emissions.

[21] Palmer C. Despite effective ban, ozone-destroying chemicals still up in the air. Engineering 2023. In press.

[22] Refrigerant data page [Internet]. Mesa: Chiller City; 2022 Feb 28 [cited 2023 Jul 25]. Available from: https://www.chillercity.com/Refrigerant_Data.php.

[23] US to ban higher GWP HFC refrigerants [Internet]. Kent: Cooling Post; 2022 Dec 10 [cited 2023 Jun 30]. Available from: https://www.coolingpost.com/world-news/us-to-ban-higher-gwp-hfc-refrigerants/.

[24] Honeywell continues transition to next-generation refrigerant in collaboration with trane technologies [Internet]. Morris Plains: Honeywell; 2021 Jun 29 [cited 2023 Jun 30]. Available from: https://www.honeywell.com/us/en/press/2021/06/honeywell-continues-transition-to-next-generation-refrigerant-in-collaboration-with-trane-technologies.

[25] Fowlie F. Fighting climate change with heat pumps [Internet]. Berkeley: Energy Institute at HAAS; 2022 Sep 6 [cited 2023 Jul 23]. Available from: https://energyathaas.wordpress.com/2022/09/06/fighting-climate-change-with-heat-pumps/.

[26] Tafur-Escanta P, Valencia-Cahpi R, López-Guillem M, Fierros-Peraza O, Muñoz-Antón J. Electrical energy storage using a supercritical CO_2 heat pump. Energy Rep 2022;8(3):502–7.

[27] Spector J. Heat pumps are already ubiquitous in Asia. When will the US catch up? [Internet]. New York City: Canary Media; 2023 Mar 21 [cited 2023 Jun 30]. Available from: https://www.canarymedia.com/articles/heat-pumps/heat-pumps-are-already-ubiquitous-in-asia-when-will-the-us-catch-up.

[28] Heu CS, Jang H, Jeon J, Lee KS, Kim DR. Recent progress on developing anti-frosting and anti-fouling functional surfaces for air source heat pumps. Energy Build 2020;223:110139.

[29] Jenkins LM. A window heat pump project is bringing cutting-edge climate tech to New York public housing [Internet]. San Francisco: Protocol; 2022 Aug 5. [cited 2023 Jun 30]. Available from: https://www.protocol.com/climate/gradient-nycha-heat-pumps-queens.