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Joule

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Commentary

Coming in from the cold: Heat pump efficiency at low temperatures

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Heat pumps have emerged as a key tool in the global transition toward clean and reliable energy and have been identified in multiple net-zero scenarios as the most important future heating technology.[1] A question frequently raised is how well these devices perform when temperatures drop below freezing, as some commentators and the media have repeatedly suggested that heat pumps cannot deliver useful efficiencies at lower temperatures.

This commentary responds to this question by analyzing field studies with real-world performance data of air-source heat pumps. It finds that well below 0°C, heat pump efficiency is still significantly higher than fossil fuel and electric resistive heating systems at an appliance level. The standard heat pumps investigated in this commentary demonstrate suitable coefficients of performance for providing efficient heating during cold winters where temperatures rarely fall below −10°C, i.e., most of Europe.

In extreme cold climates, such as where the lowest temperatures approach −30°C, performance data have shown that heat pumps can provide heat at efficiencies up to double that of resistive heating; however, more analysis is required. Even though heat pump efficiency declines during the extreme cold and back-up heating may be required, air-source heat pumps can still provide significant energy system efficiency benefits on an instantaneous and annual basis compared with alternatives.

Background

Air-source heat pumps typically use electricity to drive a refrigeration cycle that moves heat from a colder source to a warmer destination. One important aspect of measuring a heat pump's performance is its efficiency. Other technical attributes relevant to performance, such as heating capacity, are not covered in this commentary.

Heat pump efficiency is measured by the device's coefficient of performance (COP), the ratio of the useful heat outputted to energy consumed. Typical COP values for heat pumps lie in the range of 3–6, indicating that 3 to 6 units of heat are created from each unit of electricity used. A year-round average COP of 3–4 is common for household applications.

The temperature difference between a heat pump's source (the outside air) and sink (heating supply location) plays a determining role in the COP and, therefore, its overall performance. If the source temperature dips and the sink temperature is maintained, the COP falls. Around freezing temperatures, air-source heat pumps also can experience a reduction in COP due to the defrosting of external components.

Ground-source heat pumps typically provide a very high level of efficiency, even during cold weather. The reason is that soil temperature does not change significantly between seasons, resulting in a higher—and more constan—COP. In addition, ground-source heat pumps do not need to expend energy on defrosting.

This commentary focuses on the performance of air-source heat pumps in mild European winters with average January temperatures above −10°C. We refer to these heating conditions as "mild cold climates", whereas those with average temperatures below −10°C in the coldest month are designated "extreme cold climates".

Penetration of heat pumps in cold climates

Heat pumps have seen increasing deployment in many countries. Intriguingly, in

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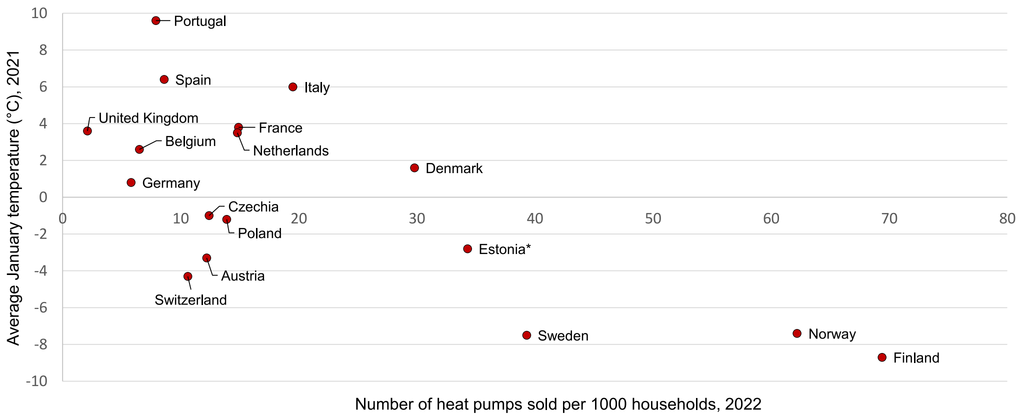

Figure 1. Heat pump sales versus average January temperatures in European countries
Figure 1 plots average January temperatures in European countries in 2021 against the number of heat pumps sold per 1,000 households in 2022, highlighting how colder climates tend to install more heat pumps.
Source: see supplemental information.
*Data for Estonia are from 2021.

Europe their use is most concentrated in countries with colder climates. These countries have installed heat pumps for decades and see the highest heat pump penetration both in terms of existing fleet and new sales, as shown in Figure 1. As of 2021, Norway had just over 60 heat pumps installed per 100 households, followed by Sweden and Finland (around 45 each) and Estonia (35), respectively.[1] These countries also experienced the highest per capita sales in Europe during 2022. The data do not provide insights about the achieved efficiency of those heat pumps, but the large share of household installations suggests that heat pumps can effectively provide heating in colder climates.

Many countries in Europe experience relatively mild winters. From 1990 to 2020, mean January temperatures across the European Union, the United Kingdom, and Norway ranged from 9.1°C in Portugal to −9.2°C in Finland. Around 80% of European households are in countries where mean January temperatures do not fall below 0°C and 95% of households are in countries where mean January temperatures are higher than −5°C. Such climate zones are not just restricted to Europe, as the data we have analyzed for this paper highlights.

Cold-weather heat pump efficiency measured in field studies

Heat pump efficiency in mild cold climates

Our research collected raw performance data from seven different field studies, focusing on heat pump efficiency in mild cold climates. The datasets represent a range of climatic zones, heat pump models, and heat pump configurations from Switzerland (CH), Germany (DE), the United Kingdom (UK), the United States (US1), Canada (CA), China (CN) and an additional lab-testing sample from the United States (US2).[2–8]

These datasets are plotted with the average COP in relation to the average outside temperature (°C) (Figure 2). Each dot represents an observation of average COP for space heating and temperature measurements that are either instantaneous (as in CA, CH, CN, DE, and US2) or daily averages (UK and US1). The number of heat pump systems represented in Figure 2 is around 550, and there are 2,760 total measurements. The heat pumps are a mix of air-to-water (CH, DE, UK) and air-to-air (CA, CN, US1, and US2) systems. More information on the system configurations can be found in the supplemental information.

When the outside temperature was between 5°C and −10°C, the mean COP across all systems was 2.74 and the median was 2.62, sufficient to meet heating loads at much higher efficiency than fossil heating and electric resistance heat alternatives.

Heat pump efficiency in extreme cold climates

Field studies also have been conducted in extreme cold climates, which we consider to be below −10°C and approaching −30°C. In these temperature ranges, specially engineered "cold-climate heat pumps" are typically deployed. We analyze their performance results in extreme cold climate conditions.

Some of the market-leading cold-climate air-source heat pumps were tested in Finland at very low temperatures.[9] Models from Mitsubishi and Toshiba both provided COPs above 2 even at temperatures as low as −20°C. At −30°C, COPs were still between 1.5 and 2 for the Mitsubishi model and 1 and 1.5 for the Toshiba model.

In field testing carried out in Minnesota (US3), the performance of central-ducted cold-climate air-source heat pumps was measured at four different sites.[10] Three of the sites returned

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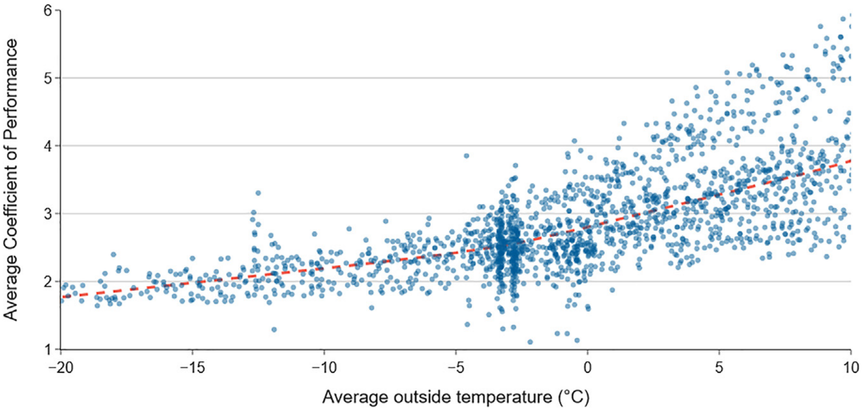

Figure 2. Air-source heat pump performance in mild cold climates from Canada, China, Germany, Switzerland, the United States, and the United Kingdom

Figure 2 plots average COP measurements versus external temperature collected from seven field-testing studies in five countries. A trendline calculated using a locally weighted scatterplot smoothing is shown.

Source: The Cadmus Group,[2] Lämmle et al.,[3] Prinzing et al.,[4] Energy Systems Catapult,[5] Safa et al.,[6] Wu et al.,[7] and Johnson.[8]

COPs between 1 and 2 during heat-pump-only operation below −12°C.

Field testing was also conducted in Alaska by the Oak Ridge National Laboratory (US4) using a cold-climate air-source heat pump.[11] These tests found that the COP remained relatively high, achieving 2.0 at −25°C and 1.8 at −35°C.

Performance summary

Figure 3 below depicts the range of COPs during mild cold climate conditions, from above 5 to just under 2. The minimum temperature point is the lowest measured temperature (albeit above −10°C) in each study. The width of the vertical "violin" indicates the number of measurements taken at that horizontal COP. The relationship between temperature and average COP is illustrated by the lower COPs seen in studies with colder temperatures. Importantly, all studies see an average COP above 2.4 between −10°C and 5°C. A summary of the heat pump performance in mild cold climate conditions (−10°C to 5°C) is shown in Table S1 in the supplemental information.

A summary of the heat pump performance in extreme cold climates is shown in Table S2 in the supplemental information. It includes the average COP at the study's minimum temperature, highlighting the performance of heat pumps in these extreme conditions.

Discussion

The studies analyzed for this commentary reveal two key findings: (1) standard air-source heat pumps can maintain average COPs between 2 and 3 in mild cold climates and (2) cold-climate air-source heat pumps can see COPs above 1.5 in extreme low temperatures, even at −30°C. Both ranges are relevant, as policies regarding heat pumps need to consider two distinct performance goals: heat pump effectiveness in meeting heating loads during both average conditions as well as short-term minimum temperatures.

The results from the field testing suggest that heat pumps are an efficient heating solution across mild cold climates. Below 0°C, the COP maintains a level well above 2 in all cases, meaning that an air-source heat pump would operate at more than twice the efficiency of combustion or resistive electric heating technology.

Strategies exist to improve heat pump performance in buildings. A key technique is reducing the heat delivery temperature. Many legacy and inefficient heating systems have relatively high water supply temperatures, in the range of 60°C–70°C.[12] Lowering these can improve heat pump performance, as the difference between source and output temperatures decreases, increasing the COP.[12] In hydronic systems, replacing just a small number of radiators to lower the required water supply temperature can greatly improve heat pump efficiency.[3]

The question whether back-up heating is needed for extreme conditions is often raised. Several of the studies included in this commentary, such as (US3), used back-up resistive or combustive heating—or at least had it available in case it was needed. However, back-up heating was typically only engaged when the outside temperature dropped past −10°C or lower. Above −10°C, heat pumps were able to provide the required heat at relatively high efficiency.

From a heat provision standpoint, this suggests that concerns over the need for back-up heating during mild cold climate conditions may be unfounded and the role for hybrid systems may be limited. There is an outstanding question over the role of hybrid systems in the coldest climates, not necessarily because of efficiency performance but because of the high output capacity of heat pumps needed at very low temperatures. Recognizing the limits of focusing only on efficiency, we suggest a valuable route for further research would be to explore the specific value of hybrid-type heating systems.

In any case, to mitigate the impact of peak heating loads on energy systems, efforts can be made toward improving the performance of the building stock to minimize load and level off heating demand peaks, as well as encourage demand response.

Some heat pumps are specifically designed for extreme cold. Though

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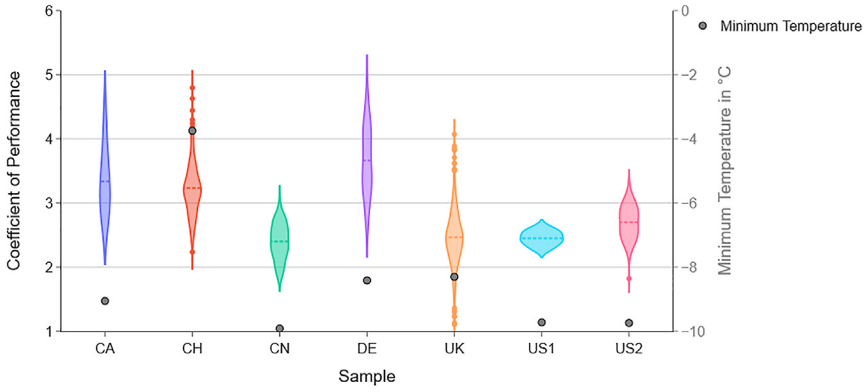

Figure 3. Range of coefficient of performance when outside temperature is between −10 and 5°C
Figure 3 plots the range of COP measurements per field-testing study, indicating the minimum temperature reached in the samples. Source: The Cadmus Group,[2] Lämmle et al.,[3] Prinzing et al.,[4] Energy Systems Catapult,[5] Safa et al.,[6] Wu et al.,[7] and Johnson.[8]

installing cold-climate heat pumps may de-risk performance in the coldest weather, there are potential trade-offs. For one, performance may suffer during milder temperatures. This is because the cold-climate systems are designed more specifically for frigid temperatures and higher heating demands. Physical components such as the expansion valve and compressor may struggle to operate at lower outputs. Strategies to address these issues can be found in the supplemental information.

Conclusions

Heat pumps are increasingly used in various types of climates to provide space and water heating. Measured performance data show that heat pumps can provide the most efficient heating in many cold climates around the world. As most European countries experience milder winters with minimum temperatures above −10°C, our analysis suggests that heat pumps can be successfully installed in these conditions without concerns over performance or the need for back-up heating capacity. This is subject to thorough heating system design and a high-quality installation in a building.

For climates that experience extreme cold temperatures, performance testing has shown that heat pumps can operate with a COP between 1.5 and 2. However, considering the related increase in heating demand and decrease in device efficiency, some form of back-up heating may be required.

Our view is that the widespread rollout of air-source heat pumps around the world as part of decarbonization efforts can be successful with existing technology in most areas that have space heating demand. Ground-source heat pumps and hybrid air-source systems may have significant value in the coldest climates.

SUPPLEMENTAL INFORMATION

Supplemental information can be found online at https://doi.org/10.1016/j.joule.2023.08.005.

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DECLARATION OF INTERESTS

The authors declare no competing interests.

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Joule, Volume *7*

Supplemental information

Coming in from the cold:
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Supplemental Information to Gibb, D. et al, Coming in from the cold: Heat pump efficiency at low temperatures

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Description of compiled datasets shown in Figure 2

In Switzerland [S01], field tests were carried out in 14 different buildings to evaluate air/water heat pump performance over a full heating season. All systems saw COPs well above 2, even between 3 and 4, around 0°C.

Field tests in southwestern Germany [S02] showed the performance of air/water heat pumps in residential applications. The heat pumps had COPs above 3 even hovering around 0°C and on the coldest day, a COP of 2.4 at -10°C.

In the United Kingdom in [S03], some of the country's coldest days with average temperatures reaching -6°C found only a marginal decline in air-source heat pump performance. Although these data contain some outlying datapoints with COPs less than 2 around 0°C, overall, the median COP was 2.4 during the coldest day of the monitoring period for all homes.

In the United States[i] [S04], 43 homes in the states of New York and Massachusetts were set up with monitoring equipment to evaluate the performance of cold-climate air-to-air heat pumps during real-world cold-weather conditions. Monitoring results showed average COPs around 2.5 when temperatures fell below freezing.

In-field performance testing of an air-source heat pump was carried out during the winter in a well-insulated house in Ontario, Canada [S05]. At the lowest outside air temperature of -19°C, COP was around 1.8, while it reached 5.0 at 9°C. Between -10°C and 0°C, COP averaged 2.75.

In China [S06], a three-month field test of an air-source heat pump system was conducted in one of the country's coldest regions. The system was able to meet the heating demand, even when the ambient temperature fell to -24°C. In mild cold climate conditions, between 5°C and -10°C, COP averaged 2.4.

Also in the United States [S07], field testing was conducted of cold-climate heat pumps in Connecticut which saw COPs above 2.5 below freezing and as high as 2.3 when daily average outside temperatures dropped to -15°C.

Due to their large sizes, the datasets CH and CN were downsampled to 500 measurements to make them more comparable to the other data. This reduced the weight of these samples in the aggregate, but their individual distributions remain the same.

Tables summarizing performance of heat pumps in mild and extreme cold climates

Table 1. Performance summary for heat pumps in mild cold climates

Study	**Average COP measured when outside temperature was between -10°C and 5°C**
[CH] – Switzerland	3.2
[DE] – Germany	3.7
[UK] – United Kingdom	2.5
[US1] – United States, NY and MA	2.5
[CA] – Canada	3.3
[CN] – China	2.4
[US2] – United States, Connecticut	2.7

Table 2. Performance summary for heat pumps in extreme cold climates

Study	**Minimum Temperature (°C)**	**COP at Minimum Temperature**
[FI] – Mitsubishi – MSZ-RW25VG	-30	1.5 – 2.0
[FI] – Toshiba – RAS-25N4KVPG	-30	1.0 – 1.5
[US3] – United States, Minnesota	-12	1.3
[US4] – United States, Alaska	-35	1.8

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[i] The authors of this study note that the data collected were not large enough to be statistically significant.

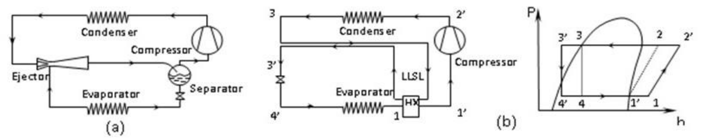
Clarifying note on heat pump performance

It is worth noting that there can be a significant range of performance across heat pumps models, due in part to the device design and in the software used to operate them. Analysing average efficiency can risk obscuring the extremes of performance and this should be considered when selecting a heat pump model that is appropriate for certain climate conditions and heating demands.

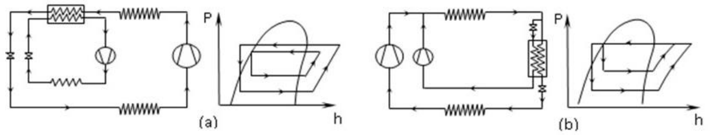
Additional information on performance enhancements for heat pumps

Strategies to enhance heat pump performance include avoiding low compressor speeds and periodically increasing speed to supply lubricant, as well as cycle enhancement, a process that increases evaporator capacity without compromising heat pump delivery temperature.

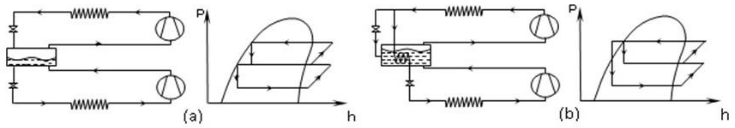
The following figures illustrate potential enhanced cycle options, whose benefits vary according to operating temperatures and refrigerant characteristics.



Cycles with ejector (a) and liquid-line/suction-line heat exchanger (b)



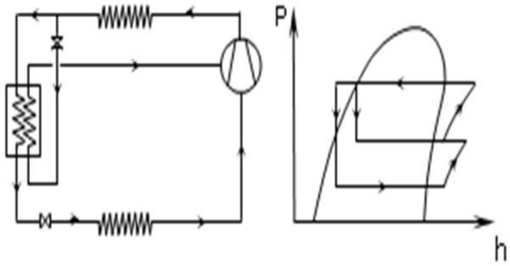
Dedicated (a) and Integrated (b) mechanical subcooling cycles



Two-stage cycles with flash tank economizer (a) and shell-and-coil economizer (b)

Figure 2: Heat Pump Cycle Enhancements

A popular approach is the use of vapour injection, where the refrigerant flow is split into two portions: the larger portion of flow works between the condensing and evaporating pressures as in a single-stage cycle, while the smaller portion of flow only works between the condensing and intermediate pressures. Thus, with not all the refrigerant flow across the whole temperature lift, performance is improved.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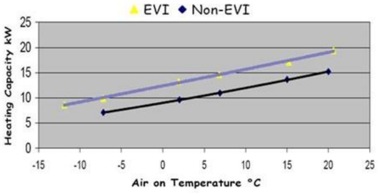
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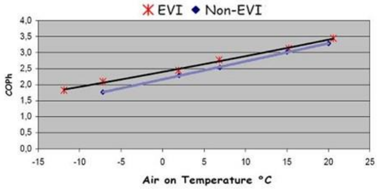
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Air on Temperature °C

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