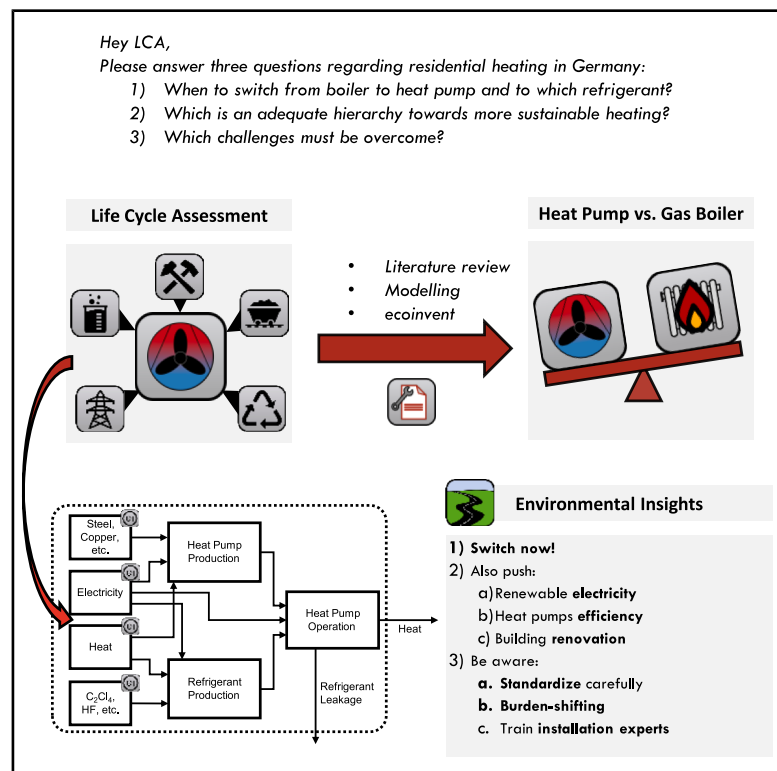


# The environmental performance of nationwide heat pump deployment in residential buildings in Germany

## Graphical abstract



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## In brief

Vering, Zibunas, et al. investigate the environmental performance of switching from boilers to heat pumps in residential buildings across Germany using life cycle assessment. The greenhouse gas reduction potential is substantial (up to –48%) and even increases when more renewable electricity is used, buildings are more energy efficient, and heat pumps become more efficient (up to –91%). However, in some categories, burden shifting occurs, revealing research needed beyond climate change.

## Highlights

- Refrigerant-dependent heat pump models for life cycle assessment framework
- Case studies reveal differences in environmental performance of heat pumps and boilers
- The approach allows for environmental assessment beyond climate change
- Burden shifting occurs when switching from boilers to heat pumps, revealing research needs



## Article

# The environmental performance of nationwide heat pump deployment in residential buildings in Germany

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**SCIENCE FOR SOCIETY** Buildings in Germany are responsible for up to 40% of the country's greenhouse gas (GHG) emissions, with a large portion coming from heating systems that burn gas or oil. To cut these emissions, replacing traditional boilers with heat pumps is crucial. Although heat pumps can significantly reduce emissions, it is unclear whether they negatively affect other environmental categories. To explore the overall potential, this work analyzes the exchange of boilers with heat pumps across Germany. The GHG reduction potential is substantial (up to  $-48\%$ ) and even increases when more renewable electricity is used, buildings are more energy efficient, and heat pumps become more efficient (up to  $-91\%$ ). Additionally, when heat pumps run at high efficiency, the environmental impact of the refrigerants is comparatively small. However, in some environmental categories, heat pumps do not outperform boilers. Future research should explore whether these categories are significant and how innovative methods help reduce them.

## SUMMARY

In the heating sector, exchanging boilers with heat pumps is expected to yield significant reductions in greenhouse gas (GHG) emissions, thus being a cornerstone of the energy transition. Reinforcing GHG reductions, the F-Gas and REACH regulations restrict the use of high global warming potential and fluorinated refrigerants. However, switching to heat pumps can cause burden shifting to other environmental impact categories, potentially compromising overall sustainability. Therefore, we holistically evaluate the climate change mitigation potential and burden shifting simultaneously, providing a life cycle assessment for 16 impact categories. A refrigerant-dependent heat pump and building performance simulation model enables five sound case studies comparing mitigation strategies in Germany. Increasing access to renewable electricity is the key to mitigating climate change (up to  $-91\%$ ) and cutting burden shifting down to five categories. Renewable electricity outshines building efficiencies, heat pump efficiencies, and refrigerant choice, which should be considered when providing information for adequate energy transition incentives and regulations.

## INTRODUCTION

Heat pumps drive the energy transition in many sectors, providing significant potential for resource-efficient and sustainable heating compared with burning hydrogen<sup>1</sup> or fossil fuels.<sup>2,3</sup> In the building sector, heat pumps are expected to increasingly replace fossil heating systems such as oil and gas boilers, systematically decarbonizing the sector<sup>4,5</sup> and decreasing the dependence on oil and gas imports.<sup>6</sup> However, due to several underutilized incentives and overloaded regulations, the sales

market for heat pumps in Europe and especially in Germany is declining,<sup>7,8</sup> being a major obstacle to the energy transition. It is, therefore, necessary to counteract this trend and reassess the efforts for an accelerated and targeted energy transition.

While burning fossil fuels in boilers mainly contributes to direct greenhouse gas (GHG) emissions, the heat pump's emissions comprise direct and indirect emissions.<sup>9</sup> Emissions of heat pumps depend on many factors, e.g., heat pump design (refrigerant choice and refrigeration cycle design), the refrigerant leakage during production, operation, and disposal, the CO<sub>2</sub> intensity of the



electricity grid mix used to operate the heat pump, and the efficiency achieved by the heat pump to supply a building.<sup>10–12</sup>

In the literature, several studies either (A) focus on the potential to reduce climate change impacts by comparing heat pump setups (refrigerant choice and refrigerant cycle design)<sup>13–16</sup> or (B) focus on the impact on several environmental metrics using a fixed heat pump setup.<sup>17–20</sup> However, due to the static environmental metric or the fixed heat pump setup, the recommendations do not consider burden shifting to further environmental categories or the sensitivity of the refrigerant's impact.

Previous studies related to hypothesis (A) only assess direct and indirect GHG emissions, e.g., investigating the refrigerants' impact on heat pumps' emissions.<sup>14</sup> In particular, the assessment of GHG emissions uses the (extended) total equivalent warming impact (eTEWI) or life cycle climate performance (LCCP).<sup>13,15</sup> Consequently, other environmental categories, such as particulate matter formation, material resources, land use, and acidification, are overlooked. Moreover, the results are based on different boundary conditions, complicating a direct comparison. Thus, Höges et al.<sup>11</sup> compared the influence of the evaluation method (seasonal coefficient of performance [SCOP], TEWI, LCCP, and a simplified life cycle assessment [LCA]) on the refrigerant choice and refrigeration cycle design. Their findings show, in line with recent literature,<sup>19,21</sup> that operation-related emissions dominate the overall emissions. The refrigerant and refrigeration cycle with the highest SCOP performs best. While they use a detailed simulation model to capture all refrigerant-dependent effects on efficiency,<sup>22</sup> a comparison to other heating technologies is missing.

Compared with hydrogen, gas, or oil boilers, which mainly convert chemically stored energy, heat pumps primarily use electricity and ambient heat. For other sectors, increasing the electricity consumption has already been shown to cause environmental burden shifting, i.e., increasing the environmental impacts of other categories beyond mitigating climate change.<sup>23–26</sup> Thus, a nationwide exchange of boilers with heat pumps impacts the environment beyond climate change, potentially causing new environmental issues. In this context, pioneering work shows the potential of burden shifting when switching from gas boilers to heat pumps in the UK.<sup>20</sup> The contribution uses a fixed heat pump setup (B), which compares the technology exchange but does not capture the refrigerant choice impact on the overall assessment. Again, the conditions vary among the studies, which results in inconsistent and partly even contradictory results.

In particular, the switch from boilers to heat pumps in the UK in Sevindik et al.<sup>20</sup> and Slorach and Stamford et al.<sup>27</sup> and in Germany in Vering et al.<sup>28</sup> yields different outcomes in environmental categories after the elimination of weather and building influences due to the use of different refrigerants, simplified modeling approaches, byproducts during production, and different leakage rates or different refrigerants. The differences emphasize that a harmonized study should be carried out that examines the relevant effects, yielding consistent results for a sound discussion and to provide information toward adequate incentives and less loaded regulations as an essential part of an accelerated and targeted energy transition in the building sector. Ultimately, the existing assessments do not coherently analyze the effects of trifluoroacetic acid (TFA, which is a per- and polyfluor-

oalkyl substance, PFAS) as a degradation product of several refrigerants, which is being discussed in an updated REACH regulation<sup>29</sup> and specialized literature.<sup>30,31</sup>

Summarizing the recent literature on LCA for heat pumps and their refrigerants compared with boilers in residential heating, the literature captures studies on individual, substantial findings about sustainability. However, there is a need for an approach that captures

- (A) more environmental impact categories to grasp environmental trade-offs alongside climate change mitigation and
- (B) a refrigerant-dependent heat pump and building performance simulation model to account for the impact of refrigerants on the overall assessment.

A harmonized assessment based on (A) and (B) with five case studies provides a sound basis for discussion to optimally drive the energy transition in the building sector. Therefore, this study contributes to answering the following questions:

- (1) When to switch from boiler to heat pump and to which refrigerant?
- (2) Which is an adequate hierarchy toward a more sustainable heating sector?
- (3) Which challenges are highlighted due to the in-depth assessment?

This study assesses the environmental impacts of heat pumps and refrigerants compared with conventional gas heating, also in environmental categories beyond climate change. To ensure a sound analysis, we conduct an LCA from cradle-to-grave (including refrigerant production, heat pump production, heat pump operation, the impact of refrigerant leakage during production and operation, and upstream processes, e.g., the provision of materials and energy). Due to a lack of data and information about refrigerant recovery processes and heat pump recycling, we conservatively assume no benefits from potential recycling. Concerning operation, we consider a 20-year lifetime providing space heating for the German building stock. The provision of domestic hot water is not included in this analysis. The benchmark for heat pump operation is a gas-condensing boiler, since oil boilers perform worse than gas boilers from an environmental point of view and hydrogen boilers, in general, are not a reasonable option to heat buildings.<sup>1</sup> The buildings' space heating demand is calculated via a building performance simulation model that considers weather data and typical building archetypes. Utilizing data from the census,<sup>32</sup> the parameter setup is scaled up from one single building (baseline scenario) to the spatial- and temporal-resolved German building stock adapted from Vering et al.<sup>33</sup>

To capture the interaction and impacts between heat pumps, refrigerants, and residential buildings, a refrigerant-dependent air-to-water heat pump model from Höges et al.<sup>22</sup> is used. The fluorinated high-GWP refrigerant R410A is a conventional refrigerant for the baseline scenario (single-family house located in Thüringen, heating efficiency G). To strengthen our findings, we conduct five case studies for building efficiency (e.g., insulation standard), refrigerant groups (fluorinated: R32, R1234yf; organic: R290, R600a, and R1270; and inorganic: R717), electricity grid mixes, and for different required heating temperatures

	Base scenario	building efficiency	refrigerant with highest SCOP	future electricity mix	combination of all
<b>Climate Change</b>	<b>-48%</b>	<b>-56%</b>	<b>-58%</b>	<b>-83%</b>	<b>-91%</b>
Ozone Depletion	-4%	-4%	-89%	-9%	-94%
Particulate Matter Formation	69%	43%	50%	13%	-16%
Acidification	111%	79%	80%	-19%	-47%
Photochemical Ozone Formation	-52%	-59%	-57%	-80%	-86%
Eutrophication Terrestrial	20%	1%	9%	-49%	-60%
Eutrophication Freshwater	2416%	2002%	2145%	99%	27%
Eutrophication Aquatic	66%	39%	48%	-60%	-71%
Ionizing Radiation	853%	694%	760%	1191%	863%
Ecotoxicity Freshwater	200%	154%	155%	-31%	-62%
Human Toxicity Cancer	31%	13%	12%	-38%	-58%
Human Toxicity Non Cancer	490%	409%	350%	95%	-22%
Material Resources	989%	853%	673%	345%	58%
Land Use	483%	389%	417%	186%	107%
Water Use	260%	201%	222%	358%	241%
Energy Resources	-52%	-60%	-57%	-71%	-79%

**Figure 1. Climate change mitigation potential and burden shifting**

The baseline scenario consists of a building simulation of a three-story house in Germany built on average between 1919 and 1949. The heat pump is powered by the German electricity grid mix 2019 (GE) and achieves a seasonal coefficient of performance (SCOP) of 3.5 using refrigerant R410A. “Future electricity mix” represents an electricity forecast (2045CN)<sup>34</sup> that will be introduced at a later point. The [methods](#) section explains in detail all further assumptions to calculate the environmental impact of space heating provided by the heat pump.

(i.e., radiator or underfloor heating system and varying heating curves) and regional effects in the German building stock using spatially and temporally resolved weather datasets. The case studies identify the most significant influences on the heat pumps environmental performance, yielding societal implications and potential for further research. Summing up the main findings of this study, we answer the questions:

- (1) When to switch from boiler to heat pump and to which refrigerant?
  - From an environmental perspective, now, even in very conservative scenarios, choose a heat pump instead of a boiler already today to mitigate climate change.
- (2) Which is an adequate hierarchy toward a more sustainable heating sector?
  - Push renewable electricity with corresponding grid expansion.
  - Push heat pumps with the highest efficiency, exploiting their potential (e.g., using R290 as a refrigerant based on our assessment).
  - Push renovation of buildings, reducing the demand and heating temperature.
- (3) Which challenges are highlighted due to the in-depth assessment?
  - If several refrigerants are hastily prohibited, there might be a conflict between the remaining refrigerants in products and safety standards, which must be reassessed.
  - If grid mixes, heat pump efficiencies, and building efficiencies improve, heat pump construction will have a major impact on several categories that are subject to burden shifting. Introducing a circular economy for heat pumps seems promising for exploiting the entire potential of heat pumps in buildings and reducing remaining burden shifting.
  - We need trained experts to plan, commission, and maintain efficient heat pumps, avoiding a bottleneck in energy transition in the upcoming years.

The paper is structured as follows: [results](#) shows the findings. [Discussion](#) discusses the work. [Methods](#) comprises the overall method and the modeling approaches.

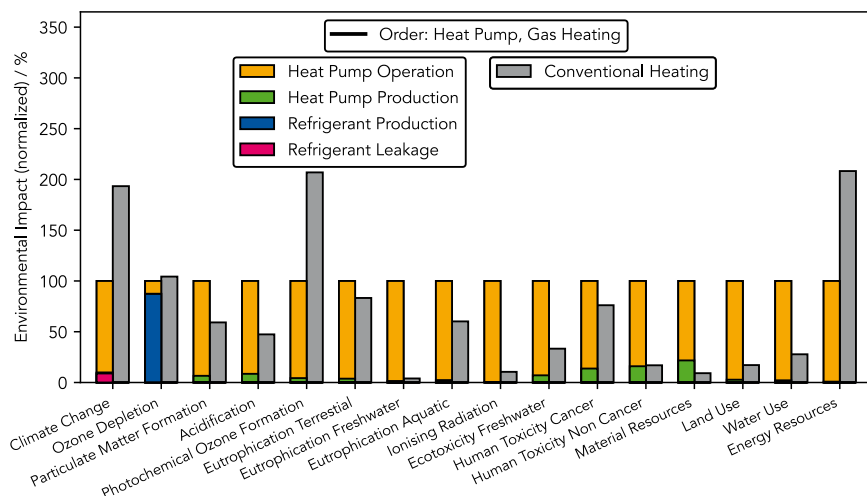
## RESULTS

### The full range of climate change mitigation and environmental burden shifting

Heat pumps can achieve a climate change mitigation potential of up to -91% compared with gas boiler heating (see [Figure 1](#)). The climate change mitigation potential, even in a very conservative baseline scenario, shows that a switch from the gas boiler to a heat pump is beneficial already today. The mitigation potential in ascending order is mainly sensitive to three factors that we discuss in more detail: (1) residential building efficiencies, (2) heat pump efficiency due to refrigerant selection, and (3) electricity generation for the heat pump operation. These factors also influence the extent of environmental burden shifting (green color, [Figure 1](#)), i.e., the increase of environmental impacts alongside climate change mitigation.

Environmental burden shifting is present in all scenarios, especially in the base scenario, comprising poor building standards, a refrigerant choice that leads to a comparably low heat pump efficiency, and current electricity generation. However, simultaneously improving all three factors will reduce environmental burden shifting in 11 out of 12 affected impact categories and even eliminate it in 7 out of 12 categories, e.g., for particulate matter formation. Whether the remaining burden shifting compromises the heat pump’s overall environmental performance requires further consideration. To date, in some categories beyond climate change, it is not fully known whether additional impacts may have consequences, thus requiring further research.

Normalization and weighting factors proposed by the International Life Cycle Data System (ILCD) can be used to assess



**Figure 2. Comparison of environmental impact of heat pump and gas boiler**

For each impact category, two bars represent the environmental impact of conventional heating and the heat pump in a baseline scenario. A color code assigns the environmental impacts to the respective stages of the life cycle. The impacts are normalized to the impacts of R410A.

impacts across different impact categories but should not be used to compare different technologies. We included the single impact scores in the [supplemental information](#). To better understand the differences in environmental impacts of heat pumps and gas boilers, an in-depth assessment of the base scenario and its sensitivity to the three factors (contribution analysis) is required.

### Case study 1: Contribution analysis of base scenario: Heat pumps vs. boilers

Figure 2 shows the contribution analysis of environmental impact from space heating provided by a heat pump and a conventional gas-condensing boiler in the baseline scenario. The baseline scenario consists of a building performance simulation of a conservatively chosen three-story house in Thuringen (Germany, a cold region for conservative assessment) with a very high annual heating energy demand of 82 MWh/a and a very high specific annual area-based heat demand of 295 kWh/(m<sup>2</sup>\*a). The heat pump is powered by the German electricity mix 2019 and achieves a SCOP of 3.5 using refrigerant R410A. All further assumptions needed to calculate the environmental impact of space heating provided by the heat pump are explained in detail in the [methods](#) section.

Using the conservative base scenario (Figure 2), the heat pump almost halves (−48%) the climate change impact of conventional gas heating, making heat pumps promising to support climate goals for residential heating already today. The reduction corresponds to 208 tons of CO<sub>2</sub> over the 20-year life cycle of a single heat pump. Applying this reduction to Germany’s residential heating demand would mitigate 65 Mt/a, 8% of the annual German climate change impact.

For the heat pump, climate change impacts are mainly caused (90%) by electricity consumption during operation (yellow). The remaining climate change impact can be attributed almost exclusively (9%) to refrigerant leakage during operation (red), owing to the global warming potential of R410A (global warming potential, GWP = 2088; details in [methods](#) section). Thus, the change to low-GWP refrigerants following F-Gas regulation is target-oriented regarding climate change mitigation.

As for climate change, electricity consumption during operation is the highest contributor for all other impact categories (78%–99%), except for ozone depletion. The second biggest contributor is the heat pump construction (up to 22%). The construction impacts human toxicity and material resources mostly due to the extraction of metals like copper that are used for heat

pump construction. Refrigerant production only significantly impacts ozone depletion (87%) (blue). Its impact results from leakage of ozone-depleting substances during the production of R410A, such as R113 or R124. R410A itself is not an ozone-depleting substance, and thus, leakage during the operation does not contribute to ozone depletion. Moreover, the overall impact of ozone depletion is 94% lower than a heat pump operating with the ozone-depleting refrigerant R22 (see [supplemental information](#); Figure S2), which was banned, compromising environmental sustainability. Achieving a lower impact and even improving compared with the gas boiler indicates that the choice for R410A is a reasonable intermediate step. Further potential can be achieved by selecting other refrigerants.

Besides climate change, ozone depletion, photochemical ozone formation, and energy resources, in Germany in 2019, the heat pump had higher environmental impacts than the gas boiler, considering recent production and operating conditions. Since the dominant share of emissions is related to the grid mix, heat pumps already perform better in 2025 in Germany or in countries with better grid mixes. Therefore, pushing green electricity helps heat pumps improve their environmental performance. Ultimately, future research must determine whether burden shifting in some categories compromises environmental sustainability, i.e., impacts transgress their corresponding sustainability thresholds (see [discussion](#)). Nevertheless, as the largest share of the heat pump’s environmental impacts can be attributed to electricity consumption during operation, the impact increase compared with the gas boiler can be traced back to the German grid mix used in the base scenario.

### Case study 2: What is the hierarchy for the energy transition?

The results of the LCA highlight that emissions attributed to electricity demand during operation account for the largest share of environmental impacts. Reducing the impacts caused by electricity demand should receive the most attention to decrease

the heat pump's environmental impacts and mitigate burden shifting. Either of the two strategies can reduce impacts:

(1) Reducing specific impacts caused by the provision of electricity.

(2) Reducing overall electricity demand with higher efficiencies.

The energy transition is expected to reduce specific emissions of electricity and, thus, reduce the environmental impacts of heat pumps. Additionally, increasing the heat pump's efficiency (e.g., measured in *SCOP*) will lower the heat pump's energy demand and reduce environmental impacts. Typically, *SCOP* depends on factors like ambient temperature that can hardly be influenced but also on adjustable design parameters, such as refrigerant selection<sup>35–37</sup> and required heating temperature.<sup>38,39</sup> Lower room temperatures or better insulation of buildings could also reduce the heat pump's electricity demand by reducing overall heat demand. However, the lower heat demand would not affect the ecological comparison between heat pumps and gas heating, which we focus on in this study. Thus, reducing the heat demand is outside the scope of this analysis but should be considered one of the most critical measures for mitigating the heating sector's GHG emissions.

The heat pump's environmental impacts in the baseline scenario were calculated assuming the German electricity mix from 2019 (GE) for the heat pump's entire lifetime (Figure 2). However, considering that Germany aims for an energy transition toward carbon neutrality by 2045, the share of renewable energies in electricity production is expected to increase. Accordingly, the impact of electricity generation and, thus, the contribution to the heat pump's environmental impacts will decrease in all except two categories: ionizing radiation and water use.

To account for the energy transition, we use a scenario from the think tank Agora Energiewende that achieves carbon neutrality by 2045.<sup>34</sup> Assuming a linear transition from the current grid mix to the projected grid mix over the heat pump's lifetime, the impact of climate change decreases by 40% on average over its lifetime compared with the current grid mix (Figure 3, GE-to-2045CN). This transition scenario approximates the average grid mix and the environmental impacts of a heat pump installed today and operated for 20 years. If the heat pump is operated with the grid mix of 2045 over its lifetime, the climate change impact would decrease by 80% (Figure 3, 2045CN), highlighting the climate change mitigation potential of heat pumps.

Due to the higher share of electricity from renewable energy sources, the environmental impacts are reduced in all categories other than land use when compared with the static electricity mix from 2019. The increase in land use can be attributed to the higher share of electricity generated via ground-mounted photovoltaics, which can be identified by checking the inventory data of the technologies in ecoinvent.<sup>40</sup>

Lowering the overall impact of electricity production reduces the shifting environmental burden. However, when assuming a linear transition to the 2045 grid mix (GE-to-2045CN), the heat pump only achieves lower environmental impacts than the gas boiler in 5 categories (climate change, ozone depletion, photochemical ozone formation, terrestrial eutrophication, and energy resources). Suppose the heat pump operates with the theoretical

grid mix of 2045. In that case, the environmental impacts can be reduced in all but six of the presented categories, highlighting the lever of renewable electricity.

If the environmental impact attributed to electricity demand decreases due to a change in the electricity mix, the share of the other phases in the life cycle, such as production and end of life (EOL), increases (see discussion). Other phases of the life cycle that may be negligible in the baseline case, like the EOL use of the heat pump, need to be accounted for if overall impacts are lowered. This shift in significance can be observed, for example, in the climate change category for refrigerant leakage and the acidification category for heat pump production.

### Case study 3: Overall electricity demand

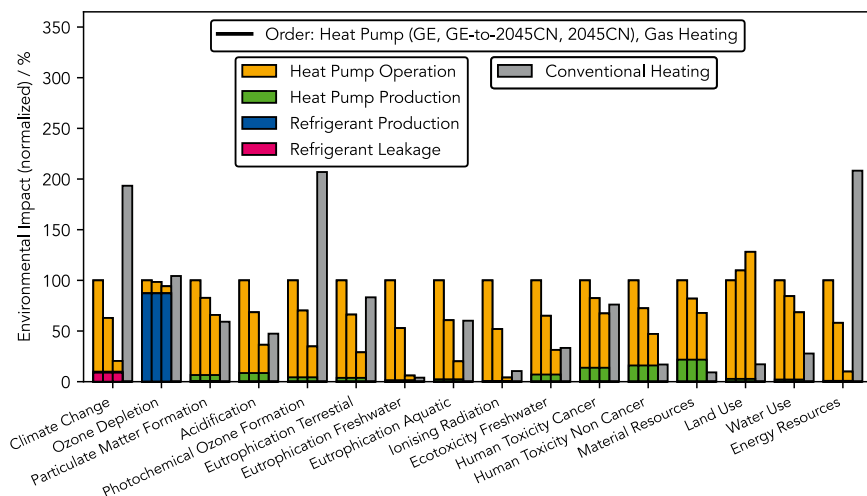
Reducing the heat pump's total electricity consumption is the second way to reduce environmental impacts due to electricity demand. The amount of electricity required for heat pump operation depends on the *SCOP*. To capture relevant influences on the *SCOP* and assess their impact on the overall environmental performance, we investigate the impact of refrigerant choice, heating temperature level (radiator or underfloor heating and heating curve setting), and heat source temperature level (regional effects).

Hundreds of refrigerants can be used in heat pumps, each with advantages and disadvantages.<sup>41</sup> In practice, the synthetic refrigerant R410A is one of the industry standards in heat pumps and, thus, chosen for the baseline scenario. Its main advantages are being nonflammable and enabling hazard-free heat pump operation while enabling acceptable efficiencies.

Using other refrigerants like propane (R290) and ammonia (R717) may lead to higher efficiencies due to their chemical properties and performance in components. However, the former is highly flammable, while the latter is toxic, requiring higher safety standards following recent regulations such as EN 378 in Europe.<sup>42</sup> Another issue currently being discussed is the use of PFAS. PFAS are a group of chemicals increasingly detected as environmental pollutants and include reaction products of the refrigerants R410A, R32, and R1234yf in the atmosphere, e.g., TFA.<sup>30</sup> There are efforts to ban these chemicals, which could further restrict the choice of potential refrigerants.<sup>31</sup>

A hasty prohibition of refrigerants may lead to a substantial conflict: a ban of several refrigerants might outlaw entire product ranges for which no alternative safe heat pump concept with flammable refrigerants yet exists or can exist, unless a reassessment of safety standards is considered at the same time.<sup>42,43</sup> Such a ban would mean falling back on conventional heating technologies instead of heat pumps, which would be worse regarding climate change. In summary, selecting a refrigerant always involves a trade-off between competing interests.<sup>36,44</sup>

In addition to the reference refrigerant R410A, we include the hydrofluorocarbon R32, the hydrofluoroolefin R1234yf, the hydrocarbons R290, R1270, and R600a, and the inorganic refrigerant R717 (Figure 4), which all imply the need for changes in the heat pump cycle setup, such as safety equipment or steel as material. According to the methods section, the material change has a direct environmental impact. Additional safety equipment is assumed to have a lower environmental impact than all other components. Further information about these



**Figure 3. Influence of grid mix on the environmental impact of heat pumps**

Each group of colored bars corresponds to the three analyzed grid mixes: GE, GE-to-2045CN, and 2045CN. The impacts are normalized to the impacts of the heat pump only using the German grid mix of 2019 (GE). Further information about the grid mixes can be found in the [supplemental information](#).

refrigerants can be found in the [methods](#) section. The refrigerants are used in a fluid-dependent heat pump model<sup>22</sup> that calculates the *SCOP* based on given boundary conditions. Using this process model allows the calculation of environmental impacts as a function of refrigerant and the used material.

As the heat demand of the building is kept constant, any difference in environmental impact between refrigerants can be attributed to different heat pump efficiencies, the refrigerants, and the used material. The lowest *SCOP* is achieved with R1234yf (3.36), a very good *SCOP* is achieved with R290 (3.83), and the highest *SCOP* by using R717 (3.88), which is in line with recent literature.<sup>36</sup> Accordingly, the electricity demand of the heat pump operation can be reduced by choosing refrigerants, such as R290 or R717, which enable higher efficiencies than R1234yf. Owing to the reduction in electricity demand, R290 or R717 improves the climate change impact by 10% and 16% compared with R410A.

In addition, the refrigerant choice can also affect other contributors to the environmental impacts aside from electricity consumption. Switching from the high-GWP refrigerant R410A to low-GWP alternatives like R290 or R717 can save additional GHG emissions caused by refrigerant production and leakage. Eliminating synthetic refrigerants such as R410A, R32, and R1234yf and using natural refrigerants like R717 significantly reduces environmental impacts in ozone depletion by eliminating the use and occurrence of ozone-depleting substances containing chlorine or fluorine during the production process of synthetic refrigerants. Using R717 instead of the other refrigerants included in this analysis also reduces impacts attributed to the heat pump's production. As R717 attacks copper and copper alloys, using copper for piping and heat exchangers is not reasonable. Avoiding copper and using stainless steel instead decreases the environmental impact of the heat pump's production in all impact categories (see decrease of green bars for R717, [Figure 4](#)). However, using stainless steel might increase the heat pump's costs, reducing sales in the long term.

As seen in [Figure 4](#), the refrigerant choice influences the overall impacts of heat pumps. Some refrigerants might be more

beneficial in lowering impacts in specific environmental categories than others while increasing impacts in another impact category. However, using R410A is not the best environmental choice, as other refrigerants like R717 can decrease climate change impacts by up to 18% without encountering environmental trade-offs. Still, we continue to focus on

R410A to conservatively assess the environmental potential of heat pumps when shifting to different heat transfer systems (radiators and supply temperatures).

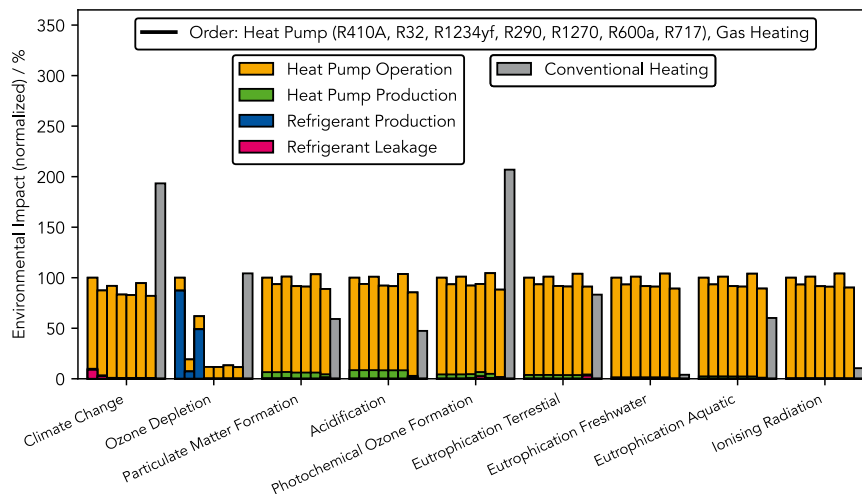
#### Case study 4: Reduce the heating temperature

The next case study comprises the heating temperature of the heating cycle. A heat pump operates by collecting heat from the outside at a low temperature level and emitting heat at a higher temperature level that is high enough to provide space heating. The high-temperature level is usually determined by the heating temperature inside the radiator and heavily influences the achievable heat pump efficiency. The higher the temperature difference between the ambient and heating temperatures, the poorer the achievable efficiency. By contrast, minimizing the temperature difference inside the heat pump increases the achievable efficiency.

The heating temperature, in turn, is determined by the characteristics of the building and the heat transfer system (e.g., radiator and underfloor heating) in which the heat pump is installed. Buildings with good insulation and low heat demand enable underfloor heating and heating temperatures as low as 35°C. Older buildings with higher heat demand often require radiators and heating temperatures up to 70°C. The differences in heating temperatures then influence the achievable heat pump efficiencies.<sup>38,45</sup>

German buildings' insulation standards and energy efficiency are categorized via efficiency standards and range from A+, buildings with very good energy efficiency, to H, primarily old buildings with subpar insulation following valid law "Gebäudeenergiegesetz." To analyze the impact of heating temperature, we show the impact of different efficiency standards (heating curves), which correspond to higher heating temperatures. To single out the impact of the heating curve, the heat demand for all buildings is kept constant.

Across all categories, environmental impacts decrease by 2%–19% ([Figure 5](#)) for the efficiency standard G compared with A, as the *SCOP* improves nonlinearly from 3.5 to 4.3. Due to the change in efficiency, the impact of climate change can



**Figure 4. Influence of refrigerant choice on the environmental impact of heat pumps**

Each colored bar corresponds to one of the seven analyzed refrigerants. Only impact categories with a recommendation level of 1 or 2 according to the ILCD are shown. Further information about the refrigerants and the full diagram, including all impact categories, can be found in the [supplemental information](#).

be reduced by 16%. Optimizing the heating curve by minimizing the flow temperature is another promising option to lower the overall environmental impact. However, user comfort should be maintained by lowering the heating temperature to allow for a fair comparison between the gas boiler and the heat pump.

Lower heating temperatures also positively influence the efficiency of gas heating systems, which, in turn, reduces the environmental impact. However, the advantages of lower heating temperatures are not as high as with heat pumps. While the heat pump achieves a lower climate change impact than the gas boiler regardless of the chosen heating curve, adapting the heating temperature is insufficient to eliminate burden shifting in any impact category that was affected previously.

### Case study 5: Impact of regional differences on heat pump efficiencies

As shown, differences in building characteristics can influence a heat pump's ecological evaluation. These differences should be considered as part of the decarbonization of the German heating sector. Additionally, especially when investigating air-source heat pumps, there are regional differences in Germany's building stock and the occurring weather.<sup>33</sup> For example, the average year of construction and, thus, the average insulation standard can differ depending on the federal state.<sup>32</sup> Furthermore, there are also differences in the average outdoor air temperatures that should be accounted for. Both factors influence the achievable efficiency of a heat pump. In the following section, we have, therefore, taken a closer look at the building stock of Germany and the regional differences.

Owing to differences in local ambient temperature, heat pumps achieve a climate change mitigation potential between 48.2% (T, [Figure 6A](#)) and 52.2% (SH, [Figure 6A](#)). Thuringen has lower ambient temperatures, resulting in higher heating temperatures and a higher temperature difference in the heat pump. The higher temperature difference negatively influences the achievable SCOP. Thus, the heat pumps in Thuringen and, e.g., Schleswig Holstein achieve different SCOPs of 3.5 and 3.79, respectively. The spatial difference in ambient temperature, therefore, has an impact on climate change mitigation po-

tential. Still, the analysis indicates a better environmental performance of the heat pump for overall Germany than in the baseline scenario, where we conservatively use the weather data of Thuringen.

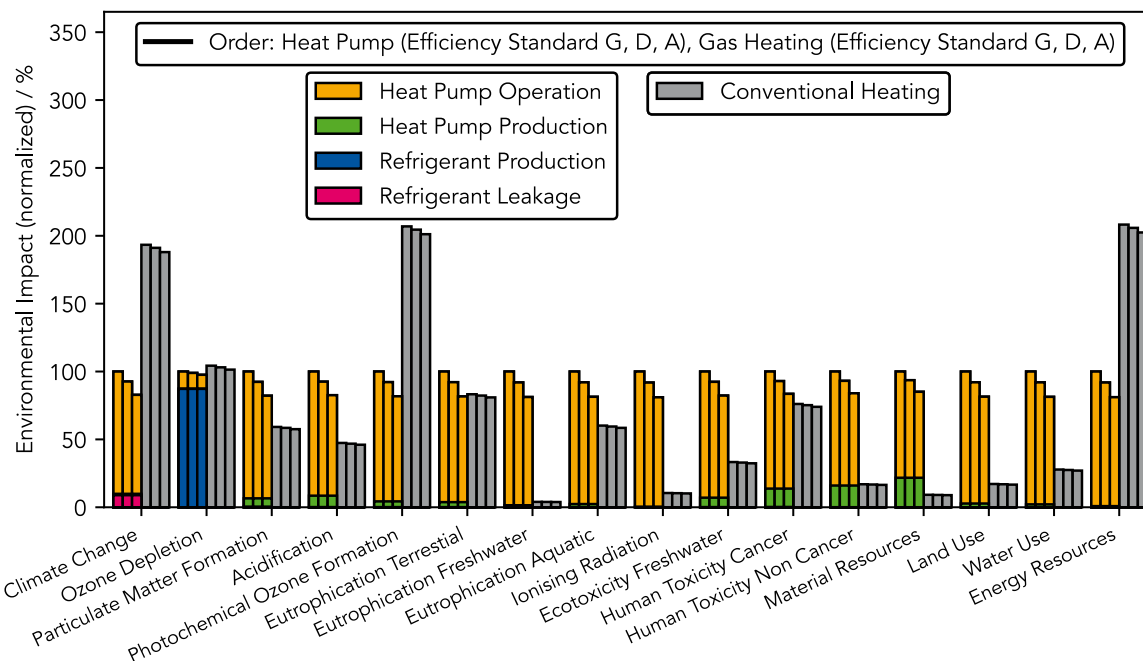
In [Figure 6B](#), we consider spatial differences within the composition of German

building stock. Using census data,<sup>32</sup> we model the composition of the building stock according to the building age. Different materials have been used depending on the building age, accounting for different insulation performances. While the building substance and the corresponding insulation standard before World War 2<sup>nd</sup> were comparably high, buildings in the immediate post-war period had poorer insulation standards, as they increasingly had to build with rubble. Since then, the insulation standard has increased, requiring lower heating temperatures to satisfy buildings' heat and temperature demands.<sup>33</sup> We perform eight building simulations for each of the 16 federal states with typical characteristics where the building age and insulation standard are varied. Image (B) data are calculated by averaging each of the eight simulations according to the building age allocation in each federal state following.<sup>32</sup>

By considering different building ages, the average climate change reduction potential is increased as we include newer buildings where better insulation enables higher heat pump efficiencies. Differences between the federal states are raised slightly. Still, the difference between the federal states with the highest (SH, -53.8%) and lowest (T, -49.4%) average reduction regarding climate change is 4.4%. Spatial differences in Germany, therefore, do influence the climate change mitigation potential of heat pumps but not as much as the energy transition or refrigerant choice. However, it is possible to achieve higher climate change mitigation today if heat pumps are installed where there is the greatest potential (high average outdoor air temperatures, reasonable insulation standards, and lower heating curves). Ultimately, current incentives need to consider these conditions and, thus, entirely exploit an accelerated and targeted energy transition. Besides pushing heat pumps into the market, we need to push building renovation waves, lowering the heat and temperature demand and thus exploiting the maximal heat pump potential.

### DISCUSSION

In this work, we carried out an LCA about air-water heat pumps. The results show that the largest share of environmental impacts



**Figure 5. Influence of heating curve on the environmental impact of heat pumps**

Each colored bar corresponds to three building efficiency standards, which correspond to three heating curves. The [supplemental information](#) provides further information about the heating curves used and the modeling of the gas boiler.

in the life cycle is due to electricity demand during operation following.<sup>19,21</sup> Other phases of the life cycle only have a secondary impact today. Therefore, efforts to minimize overall impacts should focus on electricity demand. The environmental impact of electricity demand can be further reduced by purchasing low-emission electricity, making a suitable choice of refrigerant, aiming for the highest heat pump efficiencies, and lowering heating and temperature demands.

A comparison of impacts between the heat pump and a gas boiler confirms the climate change mitigation potential of heat pumps for all refrigerants: already today, a heat pump can mitigate 48% of the climate impact of a gas-condensing boiler (Figure 2). Burden shifting increases environmental impacts in 12 of 16 categories. However, the results highlight further potential from future energy transition, enabling 83% climate change mitigation compared with a gas boiler (Figure 2) and reducing burden shifting to only 6 of 16 categories. Finally, the refrigerant selection and regional differences within Germany's weather and building stock affect the environmental performance, thus highlighting additional levers.

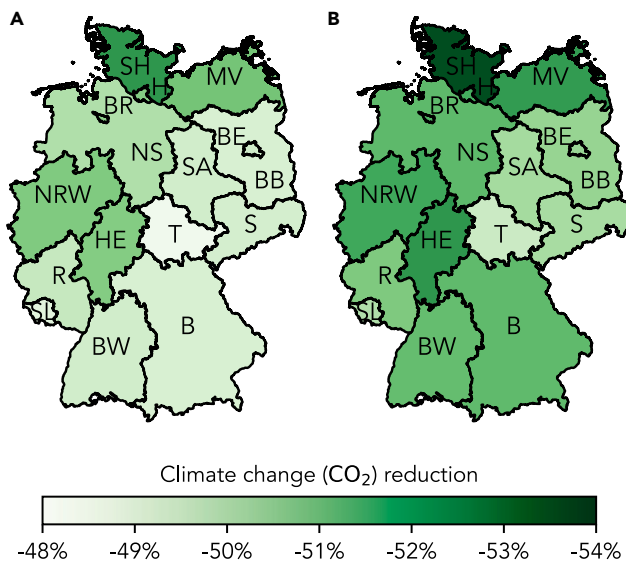
### Potential for future research

This paper analyzes the environmental performance of exchanging boilers with heat pumps in German residential buildings. The analysis is based on assumptions of each life cycle stage derived from literature. In the following, we will discuss areas for further research and their implications for the results: (1) simulation model setup, (2) grid mix assumption, (3) construction, (4) further data for life cycle inventory (LCI), and (5) overall comparison.

To simulate the operation stage of the heat pump properly, we employ a refrigerant-dependent heat pump and a building performance simulation model setup (1). The starting point of our analysis is the building model, which calculates the heating demand that the heat pump must provide. Currently, the model covers only the need for space heating, which has a higher share than domestic hot water production. Future work could consider domestic hot water supply to reflect the residential heating demand better, thus enhancing the calculation of the heat pump's environmental impact mitigation potential in absolute terms. Still, the integration is not expected to alter the comparison between gas boilers and heat pumps significantly.

The refrigerant-dependent heat pump model covers the building's heating demand and calculates the corresponding electricity demand. In this context, we conservatively neglected the positive impact of storage technologies on heat pump efficiency,<sup>46</sup> the impact of control strategy,<sup>47</sup> and the impact of optimal design on heat pump (systems) efficiency.<sup>48</sup> On the contrary, other factors, such as the improper design and installation of heat pumps and other inefficiencies of the heating system could negatively affect the actual heat pump efficiency.<sup>49</sup> In follow-up research, we recommend investigating the impact of optimally designed storage technologies and optimal control strategies to reduce the environmental impact further by increasing the heat pump's SCOP. In addition, governments must promote training on the proper design and installation to achieve the maximum from every heat pump system.

The results of this analysis are influenced by (2) the grid mix used to power the heat pump. We assume annual averages for the electricity's carbon footprint to account for the energy



**Figure 6. Spatial differences in Germany**

Images show the influence of regional differences on the ecological heat pump evaluation. For each federal state, weather data from the capital is used for the building simulation. (A) Shows the impact of different weather on possible climate change reduction. The building parameters are constant, including the building age (1919–1949) and the insulation standard. In addition to (A), (B) includes the regional differences in building age for the building stock of each federal state. Building age is used to approximate the building efficiency standard, the insulation standard, and the corresponding heating curves. More information about the procedure can be found in the [methods](#) section and the [supplemental information](#).

transition expected over the following decades. However, we do not account for changes in seasonal energy production. For instance, renewable electricity production could be lower than the annual average during wintertime and higher during the summer, respectively. Depending on whether it is winter or summer, the electricity's carbon footprint and, thus, the environmental performance of the heat pump would be better or worse. Hence, future research could focus on seasonal differences to improve the absolute numbers when comparing heat pumps and gas boilers.

Heat pump construction (3) is the cause of the second-largest environmental impact after the operation stage. Recycling processes have the potential to mitigate the environmental impact resulting from construction. In this analysis, we neglected recycling of the refrigerant and the heat pump's materials due to a lack of data. Since the heat pump has a higher material intensity than the gas boiler, its environmental performance might decrease relatively when integrating recycling into the LCA and aiming at a circular economy. Accordingly, the current assessment without recycling might overestimate the environmental impacts due to production. Nonetheless, as the production phase is a relatively minor contributor to today's overall impact, this overestimation does not affect the study's findings. Hence, reducing the construction phase impacts would strengthen our findings that clean energy is the most significant contributor.

Data availability is limited for recycling processes and all stages of the heat pump and refrigerants life cycle. To model

the environmental impacts of providing the heating demand, we set up an LCI (4) that enables LCA and five case studies. For this purpose, we had to make several assumptions based on the literature (see [methods](#)). Moreover, the literature sometimes does not provide evidence for all parameters, provides contradictory data, and sometimes assumes values that we could not reproduce. As a result, we have opted for more conservative values for parameters, which may lead us to underestimate the full potential of heat pumps. Further research that produces better data quality is needed to improve assessing the environmental impacts of heat pumps.

Since we analyze many impact categories and the impact of the heat pump and gas boiler are made up of different components, burden shifting often occurs. Assessing the severity of this burden shifting is difficult and should not be encompassed via a single impact score (5). Ultimately, future research is necessary to determine whether burden shifting in some categories compromises environmental sustainability or might be acceptable. In further research, there should also be detailed analyses about the building efficiency measures with its components and upstream processes. In addition, further technology such as photovoltaics, air conditioning, and electric cars could yield interesting insights into sustainability depending on user comfort and flexibility. Such research could use the planetary boundary framework to compare environmental impacts with environmental sustainability thresholds.<sup>50</sup>

### Implications: How to drive the energy transition? Heat pumps might need to be prioritized over other technologies when promoting electrification measures

Ultimately, the discussion suggests that the potential of heat pumps to mitigate GHGs and improve the environmental performance of residential heating could be even higher than shown in this study. To fully utilize the potential of heat pumps on a national scale, governments must remove barriers that impede rapid transformation.

A nationwide exchange from gas heating to heat pumps requires sufficient skilled technicians and targeted incentives and/or less loaded or even reassessed regulations. Among others, the efficient heat supply with heat pumps strongly depends on correct planning, commissioning, and fault-free operation,<sup>49</sup> which require trained experts. Despite this, the industry already forecasts a significant shortage (up to 60,000<sup>51</sup>) of trained experts,<sup>52</sup> which will compromise both rapid replacement and potential upcoming maintenance and service work. In addition, there is currently a considerable collapse in sales volumes of heat pumps driven by uncertainty among the population and underutilized incentive mechanisms.<sup>7,8</sup> Thus, governments must build confidence in the technology to meet climate goals.<sup>53</sup> In addition, pushing the roll-out implies the need to promote the training of sufficient experts and aim at targeted incentives and regulations to accelerate the planning, installation, and maintenance of heat pumps.

A widespread deployment of heat pumps comes with an increased electricity demand. The expansion of the electricity grid is, therefore, essential. An estimate for an increase in electricity for heating is up to 180 TWh (about 30% of the recent electricity consumption in Germany). To exploit the maximum

potential for carbon mitigation, heat pumps should predominantly use renewable electricity. Meanwhile, the growing market for electric vehicles has also increased the demand for electricity from renewable sources. Therefore, electricity from renewable energy sources will continue to be available only in limited quantities, so the goal must be to make optimal use of this electricity.

One metric to assess the optimal use is mitigation efficiency, measuring the mass of mitigated CO<sub>2</sub> per amount of electricity. Exchanging gas boilers with heat pumps yields a mitigation efficiency of 0.9 kgCO<sub>2</sub>/kWh<sub>el</sub> (see [supplemental information and Section S5](#)), assuming emission-free electricity, which is on par with electric vehicles (0.5–1.2 kgCO<sub>2</sub>/kWh<sub>el</sub>)<sup>54</sup> and considerably better than other Power-to-X technologies such as Power-to-Chemicals (up to 0.34 kgCO<sub>2</sub>/kWh<sub>el</sub>)<sup>55,56</sup> or an electric heater (0.25 kgCO<sub>2</sub>/kWh<sub>el</sub>).<sup>56</sup>

Considering heat pumps' high mitigation efficiency, governments may wish to prioritize them with the highest possible efficiency when promoting electrification measures in general. Overall, heat pumps are electricity-efficient regarding GHG mitigation and can decrease 10 of 15 environmental impacts beyond climate change, making them an obvious choice for improving environmental sustainability.

## METHODS

### LCA for heat pumps and refrigerants in residential buildings

This study analyzes the environmental impacts of a simple air-to-water heat pump operating in Germany. The heat pump provides space heating for a two-story single-family house over a 20-year time span. The heat pump is operated with the refrigerant R410A, and the functional unit is the building's heat demand over the observation period of 20 years.

The system boundaries ([Figure 7](#)) include the production of refrigerant and heat pump, the operation of the heat pump, any leakage of refrigerant during the operation, and upstream processes, e.g., the provision of materials and energy. This paper does not consider other parts of the building energy system, such as the distribution system, the buffer tanks, or the building envelope.

This study follows the ILCD recommendations to characterize elementary flows to environmental impacts, comprising 16 environmental impact categories, e.g., climate change, acidification, and ozone depletion. All 16 categories are assessed, while the focus lies on climate change. After determining the environmental impacts for all categories, all impacts are normalized and weighed. The ILCD publishes normalization factors attained by cataloging the total worldwide emissions for each impact category. The normalization is done by comparing the calculated emissions to the normalization factors of each impact category. Subsequently, we weigh all impacts via the weighing factors recommended by the ILCD.<sup>57</sup>

This work uses the LCA database ecoinvent<sup>40</sup> to obtain the environmental impacts of the material and energy used to produce refrigerants and construct and operate heat pumps. The ecoinvent datasets already contain the characterization models and, thus, the environmental impacts of each material or energy flow needed in this study. The environmental impacts are scaled

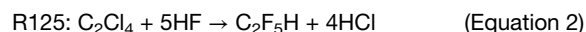
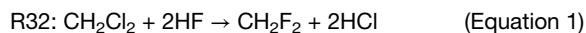
by the amount of material or energy flow necessary to supply the functional unit.

### LCA

To conduct the LCA, we need a sound basis comprising the assumptions within the calculation procedure. The reference refrigerant is R410A, but to analyze the impact of refrigerant choice, we also investigate another six refrigerants from four substance groups: R32 (hydrofluorocarbon, HFC), R1234yf (hydrofluoroolefin, HFO), R290, R1270, and R600a (hydrocarbon, HC), and R717 (natural refrigerant). Except for R717 (safety class B), all refrigerants are assigned to safety class A (cf. [Table 1](#)). However, all potential refrigerants are at least low flammable (2L and higher). To assess the environmental impacts concerning the entire life cycle, we need additional information about the production (refrigerant and heat pump), the heat pump operation, and refrigerant leakage during the heat pump operation and EOL.

### Refrigerant production

While potential environmental impacts are known and available in ecoinvent for producing natural refrigerants R290, R1270, R600a, and R717, few primary sources exist for the refrigerants R410A, R32, and R1234yf, which generally consider only GHG emissions. Therefore, for R410A (a mixture of R32 and R125) and R32 production, datasets from Frischknecht et al. are used.<sup>58</sup> Frischknecht models the production of refrigerants using chemical reaction equations with additional assumptions about the energy required, recovery, chemical leakage, and the production route. R32 (CH<sub>2</sub>F<sub>2</sub>) is produced via hydrofluorination of methylenechloride ([Equation 1](#)). R125 (C<sub>2</sub>F<sub>5</sub>H) is produced via hydrofluorination of perchloroethylene ([Equation 2](#)).

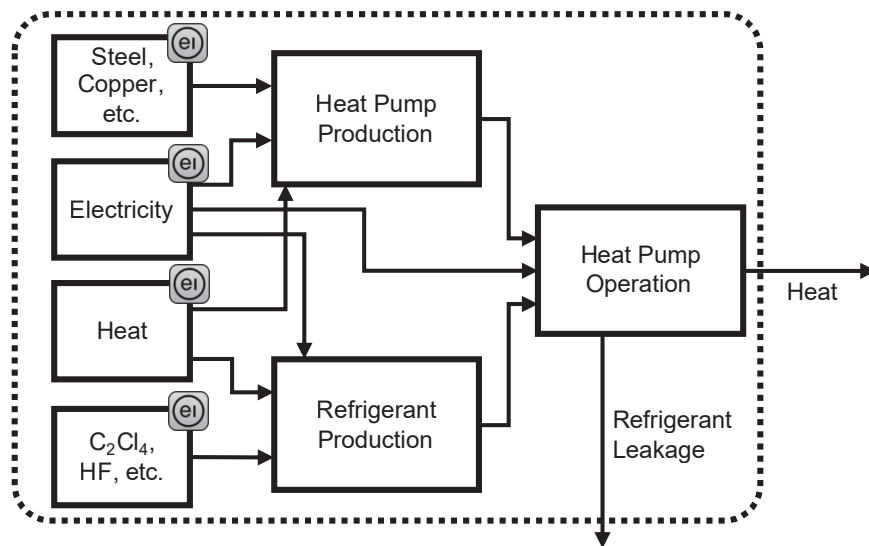


Baral and Urban<sup>59</sup> datasets are used for R1234yf production. Baral et al. study the GHG emissions from the production of R1234yf using the CHEMCAD simulation tool. The reported production process starts with the reactants chlorotrifluoroethylene and chloromethane. Moreover, leakages of chemicals, reactants, or intermediates can occur during refrigerant production. As a first estimate, an emission rate of one mass percent is assumed, comprising the reactants and intermediates.

The required charge in the heat pump depends on the refrigerant considered and determines the amount of refrigerant that needs to be produced. Commercial heat pumps for residential buildings exist for the three refrigerants R410A, R32, and R290 to access data sheets. The data sheets approximate the specific charge for R410A, R32, and R290. The specific charge of the remaining refrigerants is estimated using the UNEP report.<sup>60</sup> In addition to the amount of refrigerant required for operation, we consider refrigerant leakage that may occur during operation. The leakage reduces the heat pump's charge, so refilling the system is necessary to ensure efficiency.

### Heat pump production

The mass composition of the heat pump under study is based on a 10 kW brine-to-water heat pump from Hoval, operated with R134a. In ecoinvent data,<sup>61</sup> the masses and compositions of



**Figure 7. System boundaries for the analyzed life cycle**

The model's foreground consists of heat pump and refrigerant production, operation, and leakage. Material, chemicals, and energy provision are modeled in the background via the LCA database ecoinvent.<sup>40</sup>

the individual components are reported. The mass composition of a heat pump will vary depending on the production company and the choice of components used. Since no known mass compositions of heat pumps operating with the refrigerants were studied, the mass composition was used for all refrigerants studied except R717 (Figure 8).

R717 attacks copper and copper alloys, so copper for piping and heat exchangers is not currently approved. Since no sources on mass composition and weight of R717 small heat pumps are known, any other system technology is neglected below, and low-alloy steel's mass fraction of copper is replaced. These material compositions can be scaled to the heating power of the heating system under study using a specific weight, i.e., the total weight per heating power.

The specific weight of the heat pump depends on the design of the heat pump and the refrigerant used. The volumetric heating capacity (VHC) influences the required installation space as well as the size of the heat pump. In addition, the required wall thicknesses of the tubes depend on the maximum operating pressures of the heat pumps, which are determined by the refrigerant used. Examining data sheets of commercial heat pumps results in a specific weight of 15 kg/kW for heat pumps operating with R32 and R410A and a specific weight of 20 kg/kW for heat pumps operating with R290. Differences could not be attributed to the refrigerant and, thus, might result from design choices by the manufacturers. To the author's knowledge, no publication exists that examines the refrigerant's influence on the heat pump's weight in isolation from other influencing factors. Therefore, the

same specific weight of 18 kg/kW is assumed for all refrigerants, as it is the average of the reported specific weight based on manufacturer data. In addition to the environmental impacts from material production, we consider the heat pump's assembly and the subcomponents' manufacture using the generic ecoinvent dataset for metalworking.

#### Leakage of refrigerant

This work assumes a leakage rate  $L_{Use}$  of 5% per year in operation and a leakage

rate  $L_{EOL}$  of 30% at the end of life (EOL).<sup>62,63</sup> The total leaked refrigerant mass  $m_{RF}$  and leakage are calculated via Equation 3 using the time frame  $n$  and the refrigerant mass contained in the heat pump  $m_{RF,HP}$  (Equation 3). The characterization factors for elementary flows representing refrigerants are used to estimate the impact of refrigerant leakage. The characterization factors indicate how much the refrigerant leakage contributes to an impact category.

$$m_{RF,Leakage} = (n \cdot L_{Use} + L_{EOL}) \cdot m_{RF,HP} \quad (\text{Equation 3})$$

#### Heat pump operation

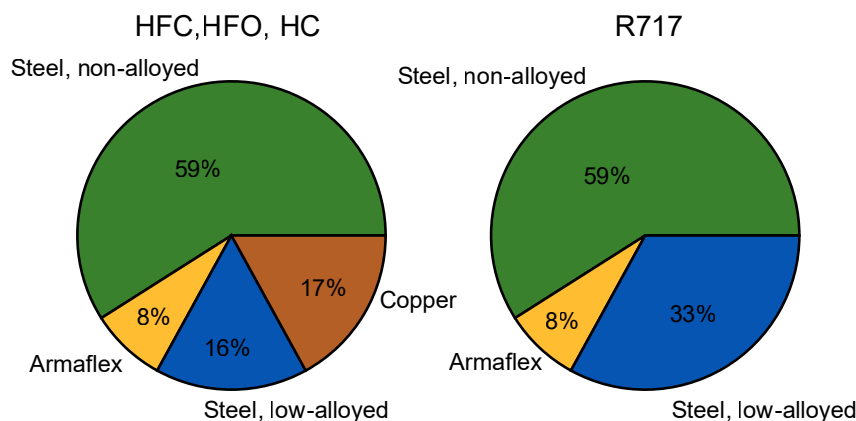
The modeling of heat pump operation has two parts. First, we have to determine the building's heat demand. Afterward, the heat pump is simulated to provide the necessary heat. The heat demand of the building is determined via TEASER.<sup>64</sup> TEASER is a framework for data enrichment of building performance simulation models to simplify simulating the heat demand of buildings, neighborhoods, and city districts. Based on the location, building type, building area, year of construction, and modernization standard, TEASER approximates the building's envelope area and insulation standard. In this paper, a three-story single-family house in Erfurt is considered. The building has a living area of 280 m<sup>2</sup>.

As the building model's boundary condition serves a weather dataset (test reference year [TRY], 2015) representing an hourly resolved annual temperature profile. The TRY dataset used represents Erfurt to match the building location and was published

**Table 1. Summary of SCOPs that were calculated and used in this analysis**

SCOP	Baseline	Sensitivity: Refrigerant					Sensitivity: Heating temperature			
	R410A	R32	R1234yf	R290	R1270	R600a	R717	A	D	G
	3.5	3.76	3.47	3.83	3.85	3.36	3.88	4.33	3.82	3.5

The reference refrigerant R410A (3.5) is used for the reference case and the grid mix analysis. The SCOP used for the refrigerant impact can be found under "Sensitivity: refrigerant," under "Sensitivity: heating temperature," the SCOP for the three assessed efficiency classes, heating curves "A," "D," and "G," respectively, are listed. The efficiency class G was also used for the baseline case.



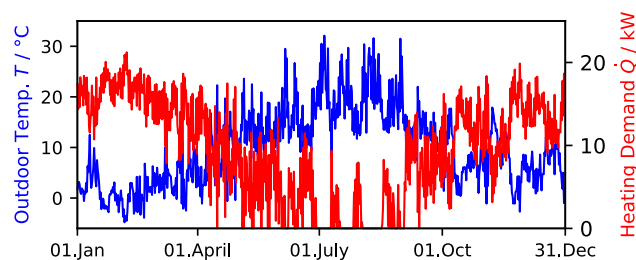
**Figure 8. Mass composition of the heat pump**

Left: mass composition of the heat pump for all analyzed refrigerants except R717. Right: mass composition of the heat pump for R717.

by the German Weather Service.<sup>65</sup> TEASER enriches a parameterized building performance simulation model with datasets and a weather dataset to create a simulation model. Then, the energetic performance is calculated based on the heat demand, which is required to balance heat losses to the environment while maintaining an indoor air set temperature, which is 21°C in our case study. In total, the annual heat demand of the considered building is about 82 MWh with a maximum heat load  $\dot{Q}_{\max}$  of 22.5 kW (Figure 9).

To meet the building's heating demand, the heat pump operation has to be modeled. We use an air-to-water heat pump model from Höges et al. to provide heat that meets the hourly resolved demand. The heat pump model includes fluid dependency and a validated loss-based compressor model and calculates the fluid behavior in the basic refrigeration cycle.

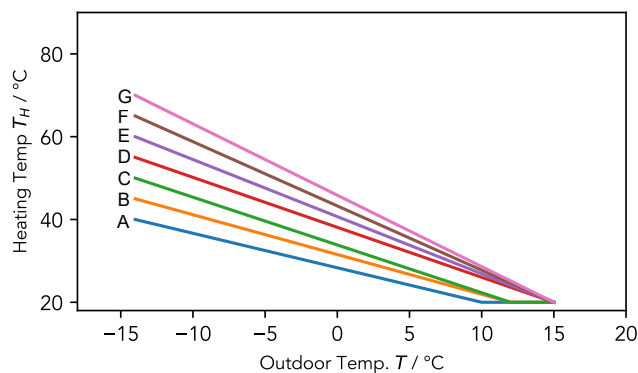
Using the outdoor air temperature and a heating curve, we determine the necessary heating temperature for the heating system. The heating curves that were used are depicted in Figure 10. The correlation between the building efficiency classes and the heating curves originates from Holm et al.<sup>66</sup> The heating curves are constructed by using two fixed points: at the heating threshold temperature according to Holm et al. (15°C for D, E, F, and G; 12°C for B and C; and 10°C for A), the heating temperature is set to 20°C. The maximum heating temperature is set according to Holm et al. and is reached at the standard outside temperature of -14°C. To isolate and compare the impact of the heating curve on heat pump efficiencies, the heating threshold



**Figure 9. Time series for outdoor temperature and heating demand**  
The blue graph displays the outdoor temperature throughout the year (source: TRY). The red graph displays the heat demand calculated by TEASER, using the outdoor temperatures as input parameters.

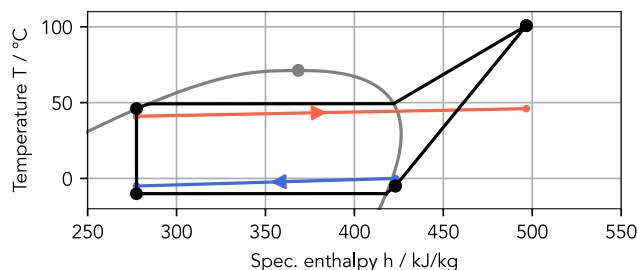
temperature has to be the same to ensure identical heat demands. Therefore, the heating curves for the efficiency classes A, B, and C are modified according to Figure 10. For the baseline scenario, the efficiency class "G" is chosen as a representative of the German building stock.

Outdoor air temperature and heating temperature serve as the boundary conditions for the calculation procedure. Based on the boundary conditions, the heat pump model (Figure 11) optimizes the pressure levels in the evaporator and the condenser. In addition, the degree of subcooling at the condenser outlet is optimized for each operating point subject to the maximum coefficient of performance (COP). The pinch point temperature difference and overheating at the evaporator outlet are set to 5 K. The temperature difference of the secondary fluids, water, and air, is also assumed to be 5 K. As all refrigerants considered cannot achieve heating temperatures above 60°C, we assume that an additional electric heater is used with a COP of 1 for heating temperatures above 60°C. The share of heat demand at heating temperatures above 60°C is less than 5% in all simulations. For more details on the heat pump model, refer to Höges et al.<sup>22</sup> Using the heat pump model, the heat demand profile, and the outdoor air temperature profile, the required electrical power and the corresponding COP for space heating is determined (cf. Table 1).



**Figure 10. Heating curves for the heat pump model**

In this analysis, seven different heating curves were used, which correspond to seven building efficiency classes.<sup>66</sup> The efficiency class and heating curve G were used for the baseline scenario and any sensitivities other than the one involving heating temperature. The section that analyzes the influence of the heating curve uses heating curves A, D, and G. In the section that analyzes spatial differences in Germany, all seven heating curves were used. More information is in the supplemental information.



**Figure 11. T-h diagram**

T-h diagram showing the change of state of R410A (black), outdoor air (blue), and heating water (red) for an outdoor temperature of 0°C and heating temperature of 45°C.

### Gas-condensing boiler

An ecoinvent dataset (see [supplemental information](#)) was used to model the environmental impacts of the gas heating system. This dataset is based on a modulating condensing boiler (<100 kW heat output). The provision of the boiler was first isolated from this dataset so that the remaining environmental impacts could be scaled using the required heat demand of the building. In addition, the efficiency of the gas heating system is modeled as a function of the supply temperature of the heating system to allow comparison to a heat pump, according to Simic et al.<sup>67</sup> The dataset is modified accordingly.

### CN2045 grid mix

We use the CN2045 grid mix published by Agora Energiewende<sup>34</sup> as part of its scenario analysis for the forecast grid mix. The environmental impact for this grid mix was calculated using the percentage shares for each technology and corresponding ecoinvent datasets. A table containing the percentage share of each technology can be found in the [supplemental information](#). The transition grid mix from the German grid mix in 2019 to the forecast grid mix was modeled by averaging the environmental impacts of the 2019 grid mix and the aforementioned forecast grid mix.

### Assumptions for analyzing regional differences in Germany

The data about the German building stock originates from the German Census data from 2011.<sup>32</sup> Census data contains, among other things, information about population and building numbers, including the composition of the building stock regarding building age for each federal state. Each building age gets assigned a representative building efficiency class using the median. The efficiency class is subsequently utilized to generate the heating curve (see [Figure 10](#)).

A TEASER simulation is carried out for each federal state and building age.<sup>64</sup> To approximate the weather in each federal state, we use weather data (TRYs) from the capital of each federal state.<sup>65</sup> TEASER approximates the insulation standard for each building age, resulting in 8 different building simulations per federal state. Afterward, the environmental impacts are calculated for each building simulation. We average the results for each federal state by using the composition of the building stock regarding building age according to the census data. Using this LCA setup, we conduct five case studies.

### RESOURCE AVAILABILITY

#### Lead contact

Further information and requests for resources should be directed to and will be fulfilled by the lead contact, Christian Vering ([cvering@eonerc.rwth-aachen.de](mailto:cvering@eonerc.rwth-aachen.de)).

#### Materials availability

This study did not generate new, unique reagents.

#### Data and code availability

This study did not generate any datasets.

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### AUTHOR CONTRIBUTIONS

Conceptualization, C.V. and C.Z.; methodology, C.V. and C.Z.; investigation, C.V., C.Z., F.T., and H.R.; writing – original draft, C.V., C.Z., and F.T.; writing – review and editing, H.R., C.H., N.v.d.A., and D.M.; funding acquisition, N.v.d.A. and D.M.; supervision, N.v.d.A. and D.M.

### DECLARATION OF INTERESTS

The authors declare no competing interests.

### SUPPLEMENTAL INFORMATION

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