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Beyond Climate Change: Sustainability Assessment of Heat Pumps and Refrigerants

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Christian Vering, Hannah Romberg, Anna Halle, Cedric Kötting, Moritz Beckschulte, Tim Klebig, Dirk Müller, Institute for Energy Efficient Buildings and Indoor Climate, RWTH Aachen University, Germany

Replacing boilers with heat pumps significantly reduces greenhouse gas (GHG) emissions, thus rendering them a vital component for the energy transition. The F-Gas and REACH regulations further support GHG reductions by limiting high global warming potential refrigerants. However, heat pumps may shift burdens to other environmental categories beyond climate change, risking overall sustainability in the long term. This study employs a life cycle assessment to evaluate the environmental performance of a heat pump using seven different refrigerants. The findings show that R290 and R717 achieve higher seasonal coefficients of performance (SCOP 3.83-3.88) than, e.g., R1234yf (3.36), reducing indirect emissions in 9 analyzed impact categories by 10-16% through lower electricity demand. As a next step, the integration of circular strategies and the compressor's lubricant into the assessment is recommended due to its interaction with efficiency in the compressor, its impact on the compressor envelope, and heat pump life-time.

Introduction

The transition from boilers to heat pumps in residential heating is critical for reducing greenhouse gas (GHG) emissions and advancing energy transition. However, despite their potential, heat pump adoption in Europe, particularly Germany, faces declining sales [1]. Heat pumps produce both direct and indirect emissions, influenced by, e.g., refrigerant choice, leakage rates, grid electricity CO_2 intensity, and system efficiency. Existing studies focus either on climate change mitigation via refrigerant choice or on broader environmental impacts with fixed setups, often neglecting burden-shifting to other impact categories. This study summarizes the findings from a previously published journal article in which a comprehensive life cycle assessment (LCA) of heat pumps and refrigerants was conducted, encompassing 15 environmental categories beyond climate change [2]. The study incorporates a refrigerant-dependent heat pump model and a building performance simulation model, which are employed to account for refrigerant impacts, operational efficiency, and building-specific heating demands.

Environmental Performance of Heat Pumps and Refrigerants

This study evaluates the environmental impacts of an air-to-water heat pump operating in a German single-family house over a 20-year period, using refrigerant R410A in the baseline scenario. The analysis follows the cradle-to-gate setup with fixed end-of-life rates in Figure 1 (left) and considers heat pump production (Figure 1, right) and operation, refrigerant production, refrigerant leakage, and upstream processes, excluding distribution systems and building envelopes. The assessment of environmental impacts is aligned with the International Life Cycle Data System (ILCD) guidelines [3].

Sixteen impact categories were calculated from which nine are presented in this study, with a particular emphasis on climate change, and using ecoinvent [4] datasets for material and energy flows. Furthermore, a comparative analysis of six alternative refrigerants (i.e., R32, R1234yf, R290, R1270, R600a, R717) in 9 out of 16 impact categories is conducted to assess their life cycle impacts, including production, operation, and constant end-of-life factors. These impacts are normalized and weighted in accordance with ILCD recommendations to be comparable with a standard gas condensing boiler.

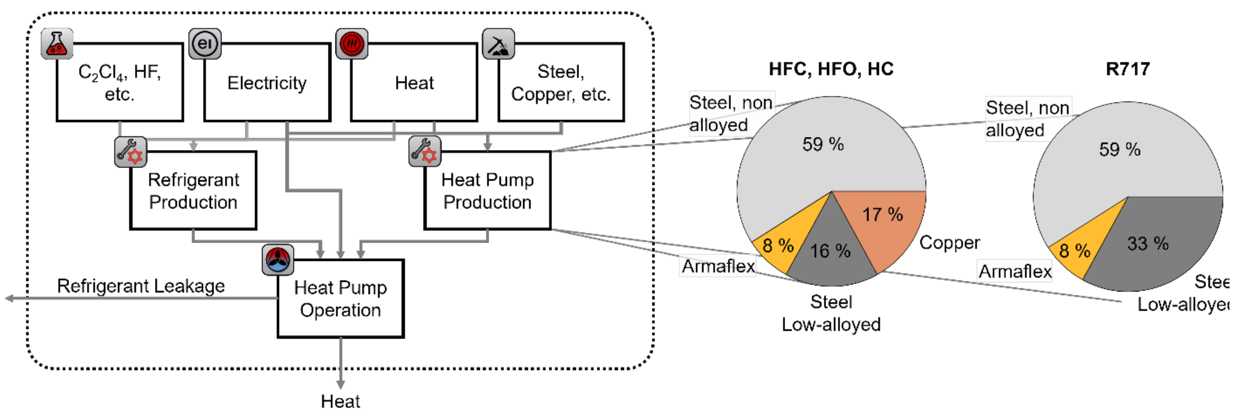

Figure 1: Process models and their interconnection during a life-cycle (left), providing heat using two different heat pump production routes based on the deployed refrigerant (right).

The life cycle inventory includes a sound data basis and modelling approaches. A detailed description of the method is presented in Vering *et al.* 2025 [2], in which the modelling of refrigerant production, including chemical reactions and leakage assumptions, is explained. Heat pump manufacturing is based on a 10 kW brine-to-water system, with material compositions (see Figure 1, right) scaled per nominal heating power and average specific weights of 18 kg/kW applied across refrigerants. Leakage rates of 5% annually and 30% at end-of-life are assumed to calculate refrigerant losses and environmental impacts. The heat demand simulation employs the TEASER framework, utilising weather data for Erfurt and a modelled three-story house with 280 m^2 living area, yielding an annual heat demand of 82 MWh and a peak load of 22.5 kW, which is provided at the national grid mix in Germany of 2020.

Hundreds of refrigerants are available for heat pumps, each with unique advantages and disadvantages. The synthetic refrigerant R410A is the industry standard due to its non-flammability and hazard-free operation, despite its environmental drawbacks due to high global warming potential (GWP). Conversely, alternatives such as propane (R290) and ammonia (R717) offer higher efficiencies but pose safety challenges due to flammability or toxicity, requiring stricter standards [5]. Additionally, synthetic refrigerants such as R410A, R32, and R1234yf have been found to produce PFAS [6], raising concerns regarding pollution and potential bans, which could potentially disrupt heat pump adoption.

This study examines seven refrigerants (see Figure 2), including R410A, R32, R1234yf, R290, R1270, R600a, and R717, utilising a fluid-dependent heat pump model to calculate seasonal performance coefficients (SCOPs) and environmental impacts compared to a gas condensing boiler. The findings reveal that R290 and R717 achieve higher SCOPs (3.83 and 3.88, respectively) compared to R1234yf (3.36), thereby reducing electricity demand and climate impacts by 10–16%. Switching to natural refrigerants like R717 also reduces ozone depletion and production-related impacts by eliminating chlorine- or fluorine-containing substances. Using stainless steel instead of copper, required for R717, further decreases production impacts but may increase costs.

Despite its reduced environmental efficiency, R410A serves as a baseline for assessing heat pump impacts under different aspects. This underscores the significance of refrigerant selection in optimizing the sustainability of heat pumps while balancing safety and efficiency.

The distinction between direct and indirect emissions is central to the environmental assessment of heat pumps. Direct emissions are caused by refrigerant leakages during production, operation, or disposal. Due to the high GWP of synthetic refrigerants such as R410A, these can make a noticeable contribution to climate change. Indirect emissions, on the other hand, result primarily from electricity consumption during operation. Therefore, indirect emissions are strongly influenced by the CO_2 intensity of the electricity mix and the system's efficiency. As part of greenhouse gas accounting (ESG-Reporting), the Greenhouse Gas Protocol distinguishes between three scopes:

- Scope 1 includes direct emissions from own sources, e.g., refrigerant leakages.
- Scope 2 includes indirect emissions from purchased energy, such as electricity consumption during operation.
- Scope 3 takes into account other indirect emissions that occur along the value chain, e.g., production of the heat pump or transport of refrigerants.

Figure 2 shows that only refrigerants with high GWP cause significant Scope 1 emissions due to leakage. Furthermore, it is evident that Scope 2 emissions dominate the environmental impact due to electricity use during operation under German grid mix conditions from 2020. Consequently, the SCOP significantly influences indirect emissions, making R717 – with its superior efficiency – particularly favorable in terms of overall environental performance. Finally, compared to the gas boiler, it is evident that burden-shifting occurs in 6 out of 9 categories. Therefore, the overall sustainability of heat pumps has to be taken into account in the future to reduce the overall environmental impact.

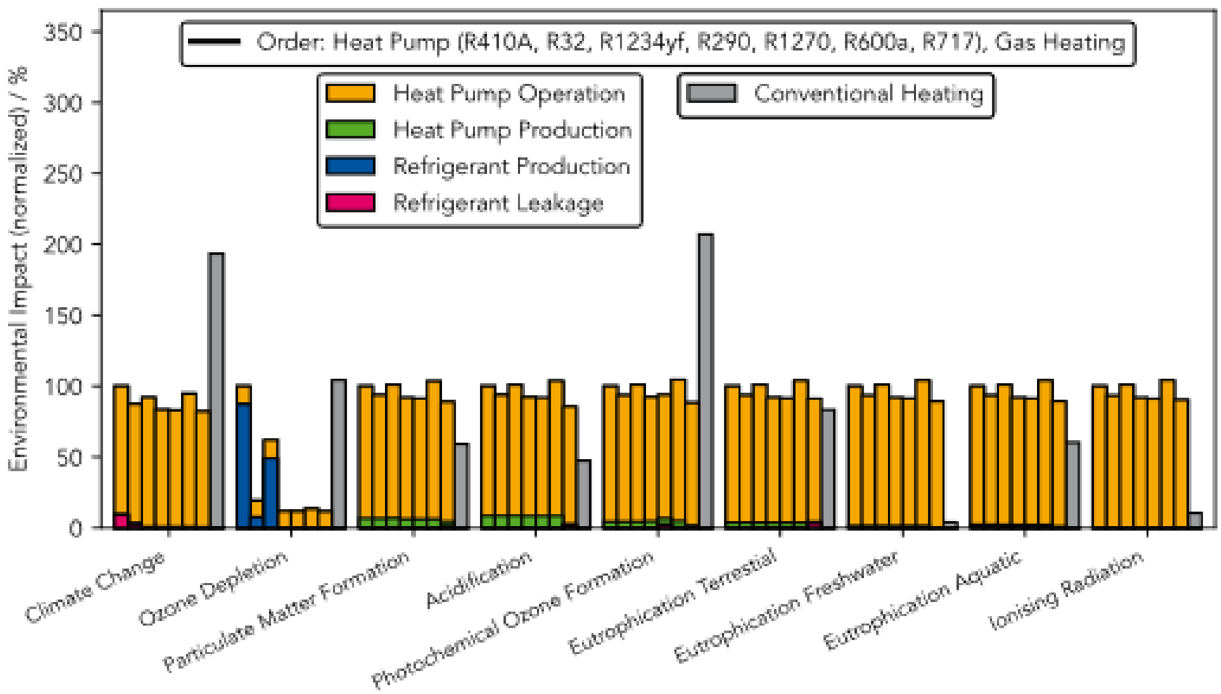

Figure 2. The environmental impacts of a heat pump are shown for each environmental category and each refrigerant (standardised to R410A). The environmental categories are according to the ILCD Recommendation Levels [3].

Limitations

Heat pumps with heating capacities of approximately 25 kW, as examined in this study, commonly utilize positive displacement compressors. These compressors are lubricated, leading to the introduction of lubricants into the heat pump LCA. Common lubricants for heat pumps include mineral oils and synthetic options such as polyalpha-olefins, polyalkylene glycols, and polyol esters. Both can be produced through petrochemical processes, yielding further Scope 3 emissions. Moreover, the choice of lubricant significantly affects both the efficiency and capacity of heat pumps. Higher viscosities result in increased friction losses while minimising losses due to reverse flows. Additionally, lubricant is injected from the compressor into the refrigerant cycle, where it can create a film on all surfaces that may insulate the heat exchangers and decrease their efficiency. Therefore, the selection of lubricant can influence the power consumption of the heat pump and its operational Scope 2 emissions. [7,8,9].

The present study has not addressed the impact of the production, handling during maintenance, efficiency impacts, and end-of-life management of lubricants, yet, which is recommended to get the bigger picture of sustainability assessment. In addition, the introduction of circular strategies compared to constant linear end-of-life strategies could be helpful, further reducing overall emissions compared to the gas condensing boiler [10].

Conclusions

This work presents an insight into an in-depth life cycle assessment of heat pumps and refrigerants compared to gas boilers. Under 2020 grid mix conditions in Germany, greenhouse gas emissions can be significantly reduced when heating a building with a heat pump. However, burden-shifting occurs, meaning that the environmental impact in other categories increases when switching to heat pumps. In this regard, the study now reveals leavers for future development: (1) provision of green electricity, (2) utilizing heat pumps with high efficiencies, and (3) changing to low-GWP refrigerants is key for minimizing environmental impacts. For future work, we recommend including the compressors lubricant and circular strategies into the assessment to get the bigger picture of LCA assessment and finding optimal solutions for refrigerant and oil combinations in heat pumps.

Author contact information

Name	Christian Vering
Affiliation	Institute for Energy Efficient Buildings and Indoor Climate, RWTH Aachen University
Postal address	Mathieustrasse 10, 52074 Aachen
E-mail address	cvering@eonerc.rwth-aachen.de
Phone number	0049 241 80 49 786

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