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ENVIRONMENTAL PERFORMANCE OF RESIDENTIAL HEATING SYSTEMS: A COMPARATIVE CROSS-TECHNOLOGY LCA

Summary

This paper presents a harmonized framework for life cycle assessment (LCA) to compare the environmental impacts of heating systems for single-family and multi-family houses. The analysis is conducted using the functional unit of 1 kWh of heat supplied to the building. The technologies examined include air source heat pumps with and without solar thermal collectors, brine-water heat pumps with geothermal probes or PVT collectors, and a pellet boiler with solar thermal support. A gas condensing boiler serves as the fossil fuel reference. The results show that all renewable systems significantly reduce the carbon footprint compared to the gas boiler. In the case of heat pumps, at least 93% of emissions occur during the use phase and are attributable to the electricity consumption from the grid, underscoring their long-term decarbonization potential by the ongoing decarbonization of the grid mix.

Keywords: Life cycle assessment, heat pump, solar thermal, PVT, pellet, decarbonization potential

Field of application for the findings: investment decisions for residential heat supply, strategic planning and policy design for decarbonizing residential heating

Addressed audience: investors, policy makers, energy planners and consultants, LCA practitioners

1. Introduction

In Germany, the heat demand in the residential sector is 586 TWh, which represents 47 % of the total national heat demand (Umweltbundesamt, 2025). The energy required for space heating contributes the largest share at almost 71%, while the energy required to cover the hot water demand accounts for an additional 17% (Umweltbundesamt, 2025). Since about 78 % of residential heating systems are still fossil-based (Becker *et al.*, 2023), this is a key area of action to achieve climate neutrality by 2045. To reach this goal, the transition to a renewable energy system is essential, requiring a broad variety of private actors to participate and replace their fossil-fueled heating systems with renewable energy technologies. The German building energy act from 2024 (Gebäudeenergiegesetz, GEG), aims to further accelerate this transition in the heating sector. It requires heating systems to be fueled by at least 65 % of renewable energy sources, while defining exceptions and transition periods (Bundestag, 2020).

Especially heat pumps have experienced an accelerated deployment in the recent years (Bundesverband Wärmepumpe e.V., 2023). The vast majority of renewable heat, however, is still provided by biomass (Umweltbundesamt, 2025). Solar thermal collectors covered less than 5% of the heat demand in Germany in 2024 (Umweltbundesamt, 2025). All of these technologies have an impact on the environment during their production and disposal phases. However, the impact during the usage phase can vary greatly. While the operational environmental impact of a heat pump is mainly due to electricity consumption, the combustion of biomass produces direct emissions. Emissions originating from the combustions of biomass are classified as biogenic (non-fossil) emissions. They are by definition climate-neutral and are not counted towards the climate change impacts. Solar thermal collectors do not cause any direct emissions during their operation.

The market for residential heating systems is highly heterogeneous and, depending on the building specifications, characterized by varying requirements. Investors face a large number of alternatives, not only in terms of the heating technology itself, but also regarding the energy carriers or fuels as well as the system configuration and sizing, while a comprehensive comparison is missing.

The conducted research project aims to fill this gap and provides both a methodological guideline on how to conduct a cross-technology comparison of heating systems as well as calculated results on the economic and ecological sustainability of selected heating systems under pre-defined conditions. In the project four different reference buildings were defined, and a heating load profile was generated. The investigated heating systems have been dimensioned accordingly, and their operation phase was simulated in PolySun. Based on these data, an economic and ecological evaluation of all systems was conducted. Selected systems were then linked in a comprehensive comparative analysis. This contribution focuses on the ecological assessment and comparison of selected heating systems.

2. Methodology

Life Cycle Assessment (LCA) is the method of choice to assess environmental impacts of products or services. DIN EN ISO 14040 and DIN EN ISO 14044 define the basic structure and minimum requirements for this methodology, while allowing for flexibility. While this enables practitioners to make the individual methodological choices to assess the product or service of their choice, it makes the comparison of results of different studies difficult or even impossible. To ensure fair and comprehensive comparability, especially across several different technologies, the harmonization of system boundaries, functional units and impact assessment methods is essential.

In order to achieve comprehensive and therefore meaningful results, the entire life cycle of the heating system is considered. To create the greatest possible added value for users, only the heating system and its components are assessed. Potential renovations of buildings (e.g., additional insulation) or the distribution system (radiators) are not within the scope of this analysis. To further increase the comparability of the results, the consumption side is standardized using representative standard load profiles. All heating technologies considered are designed to meet the heat demand of the reference buildings at all times. Existing and new single-family and multi-family houses are considered. The functional unit is set at 1 kWh of heat supplied to the building. The uniform choice of evaluation method is also crucial for the comparability of LCA results. In line with ecological assessment approaches in the building sector, modeling and evaluation are carried out in accordance with EN15804+A2.The chosen system model is “cut-off”.

The data requirements are largely covered by primary data collection from project partners, with life cycle inventory databases and literature data being used to fill in any data gaps. In addition to methodological aspects, technological parameters must also be standardized to ensure a comprehensive and fair comparison. These include, for example, the service life of heating systems and individual components, efficiency, degradation, installation location, disposal scenarios, and the electricity mix used.

The investigated heating technologies are designed to be GEG-compliant and selected according to their market relevance. These include an air-source heat pump with and without additional solar thermal collectors, a brine water heat pump using a ground probe as a source or a PVT-collector and a pellet system with solar thermal support. A gas condensing boiler is included as a reference value.

3. Results

This article presents and discusses key project results. The focus is particularly on the ecological assessment. All investigated renewable energy systems show a significant decarbonization potential in comparison to the gas condensing boiler which shows a carbon footprint of 0.291 kg CO_{2eq}/kWh_{th}. With the assumption that the current German grid mix (Burger, 2025) is used in combination with rooftop PV electricity, the air-source heat pump in the newly built single-family house shows an average carbon footprint of 0.087 kg CO_{2eq}/kWh_{th}. The addition of solar thermal collectors to the system slightly improves this carbon footprint to 0.085 kg $CO_{2eq}/kWh_{th.}$ Depending on the heat source, the brine-water heat pump systems show a carbon footprint of 0.079 kg CO_{2eq}/kWh_{th} and 0.089 kg CO_{2eq}/kWh_{th} for the ground probe and the PVT collector, respectively. The pellet system has a climate impact of 0.041 kg CO_{2eq}/kWh_{th}.

In all investigated heat pump systems, the usage phase and the associated electricity consumption from the grid dominate the carbon footprint. At least 93% of CO_2 emissions are attributed to the operation-phase. It is therefore to be expected that the ongoing decarbonization of the electricity mix will further reduce the climate impact of heat pump systems in the coming years and decades. A sensitivity analysis shows that, taking into account a dynamic electricity mix model to map the development of the electricity mix over the next 25 years, the CO_2 footprint of all heat pump systems can be significantly reduced. All investigated heat pump systems show an average carbon footprint of 0.036 - 0.040 kg CO_{2eq}/kWh_{th} when the decarbonization of the grid mix over the course of the system lifetime of 25 years is included in the assessment.

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