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# Evaluating Environmental Impacts of Domestic Heat Pumps: A Review through Life Cycle Assessment

Mona Aridi<sup>1</sup>, Marie-Lise Pannier<sup>1</sup>, Rima Aridi<sup>1</sup>, Thierry Lemenand\*<sup>1</sup>

<sup>1</sup> Univ Angers, LARIS, SFR MATHSTIC, F-49000 Angers, France  
62 avenue Notre Dame du Lac, 49000 Angers  
[\\*thierry.lemenand@univ-angers.fr](mailto:thierry.lemenand@univ-angers.fr)

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*RÉSUMÉ. Avec le besoin croissant de solutions de chauffage économiques et éco-énergétiques, les pompes à chaleur (PAC) ont émergé comme une alternative prometteuse pour les systèmes de chauffage résidentiels, jouant un rôle crucial dans le virage mondial vers une technologie de chauffage plus durable. Cet article de revue présente une analyse approfondie des techniques d'Analyse du Cycle de Vie (ACV) appliquées aux PAC domestiques, en (i) examinant la littérature existante sur les ACV menées pour les PAC domestiques, dans le but d'évaluer leur impact environnemental tout au long de leurs étapes de cycle de vie ; (ii) discutant des indicateurs environnementaux clés et des paramètres couramment évalués dans les ACV pour les PAC domestiques tels que le Coefficient de Performance et les réfrigérants ; (iii) indiquant les défis liés à la réalisation d'ACV pour ces systèmes. Cette étude met en évidence la nécessité de méthodologies normalisées et d'améliorations de la qualité des données, et propose des recommandations pour les orientations futures de la recherche afin de soutenir le développement de technologies de chauffage durables dans les structures résidentielles. En conclusion, l'ACV réalisée sur les HP révèle des perspectives précieuses pour améliorer leur impact environnemental à travers différentes étapes.*

*MOTS-CLÉS : Pompes à chaleur, Analyse du Cycle de Vie, Revue*

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*ABSTRACT. With the growing need for economical and energy-efficient space heating solutions, heat pumps (HP) have emerged as a promising alternative for residential heating systems playing a crucial role in the global shift to a more sustainable heating technology. This review paper presents a thorough analysis of Life Cycle Assessment (LCA) techniques applied to domestic HP, by (i) examining the existing literature on LCAs conducted for domestic HP, aiming to assess their environmental effect across their life cycle stages ; (ii) discussing the key environmental indicators and parameters commonly assessed in LCAs for domestic HP such as Coefficient of Performance and refrigerants ; (iii) stating the challenges in conducting LCAs for these systems. This study highlights the necessity for standardized methodologies and data quality refinements and offers recommendations for future research directions to support the development of sustainable heating technologies in residential structures. In conclusion, the LCA conducted on HP reveals valuable insights to improve their environmental impact across various stages.*

*KEYWORDS: Heat pumps, Life Cycle Assessment, Review.*

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## 1. INTRODUCTION

### 1.1. LIFE CYCLE ASSESSMENT

The concept of Life Cycle Assessment (LCA) emerged during the 1960s due to concerns about environmental deterioration, particularly limited resource availability (Amahmoud et al., 2022). Afterward, a remarkable achievement was made in standardization, with LCA gaining recognition in policy and legal frameworks. Additionally, many prominent life-cycle impact assessment techniques originated during this period. LCA experienced methodological divergence in response to increased

demand. Challenges in interpreting ISO criteria led to the emergence of various approaches (Curran, 2016) (Guinée et al., 2011). Nowadays, LCA is expanding its focus to encompass all three dimensions of sustainability – environmental, social, and economic (Amahmoud et al., 2022).

## 1.2. LCA OF HEAT PUMPS

To maintain the increase in the global temperature to 2°C, over 190 countries committed to cutting their emissions by 40% by 2030 as part of the Paris Climate Agreement (*Paris Agreement on Climate Change*, 2024). Nations are putting serious efforts into decarbonization by introducing a renewable energy source, resulting in improving the architectural style. Enhancing efficiency in appliances entails applying methods derived from nature (*2019 Global Status Report for Buildings and Construction*, 2019). Heat pumps (HP) are crucial for EU decarbonization goals. However, regular assessment is necessary to ensure their ongoing performance and minimize environmental impact.

Since 1990, LCA has been applied to the HP industry (Lis et al., 2019) (Taborianski & Prado, 2004) (Fava, 2006), and as a good diagnostic tool for monitoring the performance of products, it contributed significantly to its improvement over years. Many comparative studies have been conducted to compare the performance of HP systems to conventional ones in terms of environmental impact (Marinelli et al., 2019) (Lin et al., 2021) (Lozano Miralles et al., 2020). Various Life Cycle Impact Assessments (LCIA) were utilized to identify those impacts such as CML2001, ReCiPe, Eco-indicator 99, IPCC, EF method, and many others. Some methods assessed impact categories at intermediate levels (midpoint), while others focused on the overall environmental damage (endpoint), with some employing both levels depending on the approach of the study. Despite being energy-efficient, HP systems still contribute to the environmental impact by increasing greenhouse gas (GHG) emissions, notably the refrigerants used and carbon dioxide (CO<sub>2</sub>) emissions through the generation of electricity needed to power them.

## 1.3. OBJECTIVES AND SCOPE OF THE STUDY

This review examines existing literature on LCA conducted for domestic HP in residential buildings, evaluating their environmental impact across their life cycle stages, discussing the key environmental indicators and parameters in LCAs, and addressing the challenges in conducting LCAs for these systems. Eventually, this work aims to propose clear and objective recommendations for future action plans in the realm of heat pumps.

# 2. METHODOLOGY

## 2.1. SEARCH STRATEGY AND STUDY EVALUATION

This review evaluates the environmental impacts of domestic HP in residential buildings by examining their LCA. An electronic search was conducted on SCOPUS and Web of Science databases due to their scientific standards and extensive coverage. Key terms were formulated to initiate the research followed by an organized, phased search approach to filter out the irrelevant articles.

Criteria such as date and type were applied to narrow down the search. Only English-language research articles were considered in which they were screened based on titles and abstracts for relevance, with non-aligned or irrelevant abstracts excluded. After removing inaccessible articles and duplicates, a comprehensive full-text reading was carried out to ensure the credibility of the selected articles in terms of study design, methodology, and relevant outcomes.

The key terms used in both databases are “Domestic heat pumps” OR “Ground-source heat pumps” OR “Water-source heat pumps” OR “Air-source heat pumps” AND “Life Cycle Assessment” OR “Life Cycle Analysis” OR “LCA”, then 297 articles were addressed in SCOPUS and 169 in Web of Science, for which each of them underwent a systematic path of filtering.

Out of the English research articles that evaluated the impact of domestic HP on the environment using LCA methods during the last two decades, 36 articles were chosen and retrieved to be discussed in this review.

## 2.2. DATA IDENTIFICATION

The 36 articles under study were issued between 2010 and 2023 in which 22 of them (equivalent to 61%) were released in the last four years, between 2020 and 2023, inclusively. The box plot of the distribution of years of publication in Figure 1, is negatively skewed due to the dominance of data to the right side of the axis which resulted in a skewness to the left showing the attention that has been recently drawn to the assessment of domestic HPs using the LCA approach.

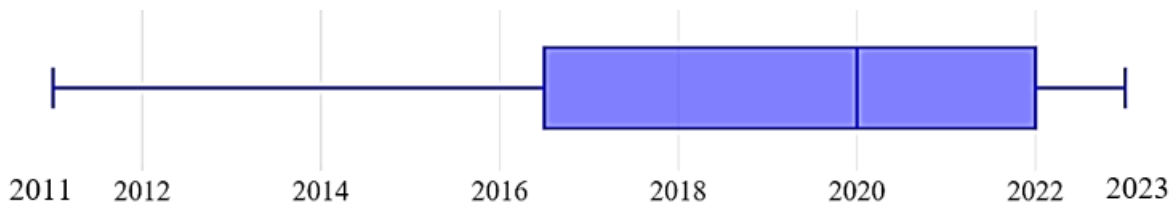


Figure 1: Boxplot for the distribution of years of publication.

Attaining environmental goals has been a serious concern for the European countries especially in the last decade and after the Paris Agreement in 2016. Eventually, most of the European countries have launched the Nationally Determined Contributions (NDCs) to reduce their GHG emissions by enhancing and improving their technologies (*Paris Agreement on Climate Change, 2024*). Most of the articles (69.5%) were carried out in European countries along with their case studies, as illustrated in Figure 2.

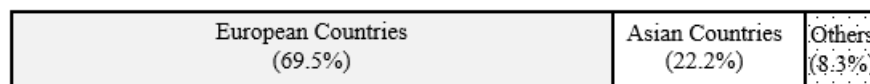


Figure 2: Distribution of articles among countries.

As each type of the studied HP may have a different impact on the environment, the 36 studied papers were classified and regrouped according to the type of HP under study. These classifications are well presented in Figure 3. Interestingly, 18 studies – equivalent to 50% of the articles – aimed to evaluate the environmental impact of Ground-Source Heat Pumps (GSHP) and Geothermal Heat Pumps (GHP), in which six of them compared the GSHP with Air-Source Heat Pumps (ASHP), and five other studies compared the GSHP with conventional heating systems such as condensing natural gas, biomass, and coal boilers. Finally, seven studies assessed the GSHP without comparison.

Four studies compared the ASHP to conventional systems and only one study focused on ASHP without any comparison. A group of five miscellaneous types of heat pumps were investigated in comparison with another system. Another group of eight miscellaneous types of HP was compared to conventional systems.

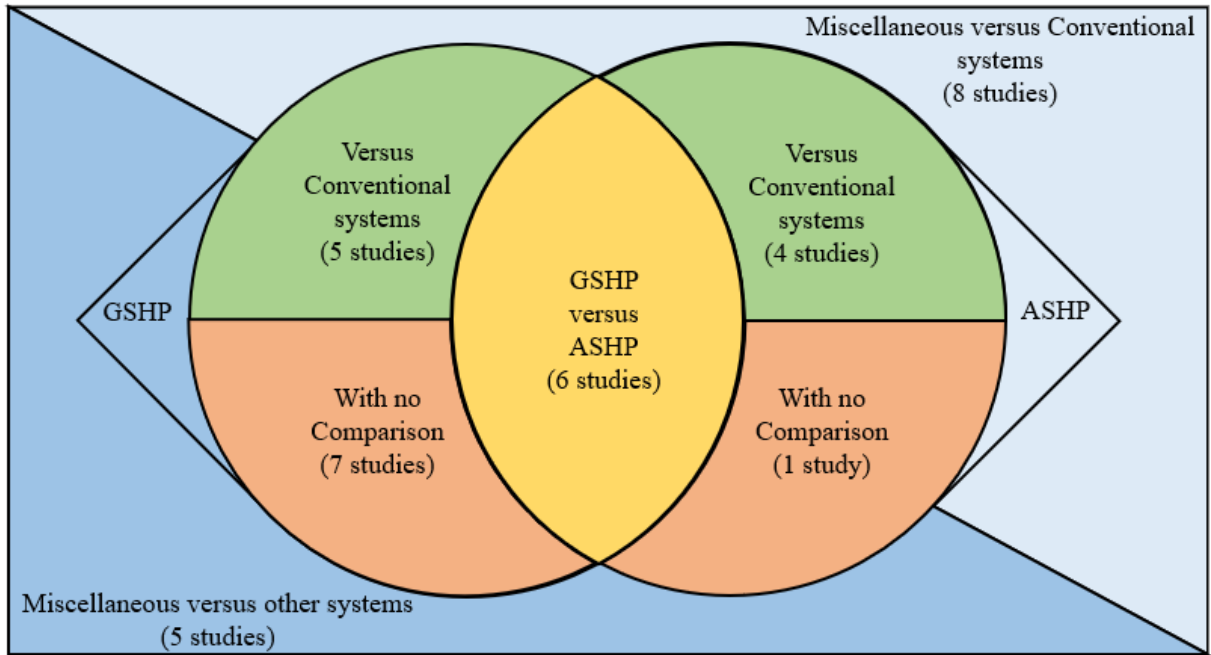


Figure 3: Classification of articles according to the type of heat pump.

These seven classifications are compared and examined in terms of their load on the environment. It should be noticed that none of the articles were about double service heat pumps.

### 2.3. DISSIMILARITIES

Comparing these 36 articles was challenging as dissimilarities took place among the factors that should be comparable, such as the refrigerants, the Coefficient of Performance (COP), the functional unit, and the Life Cycle Impact Assessment (LCIA) method.

**Refrigerants.** The type of refrigerant used in the HP systems considerably affects the system environmental impacts. However, it was not available in all studies in which 13 studies (accounting for 36%, as shown in Table 1) didn't mention the type of refrigerant used. Ignoring the contribution of refrigerants to the environmental load created an essential dissimilarity. However, for the studies that defined the refrigerants being used, the environmental impacts of refrigerants vary based on factors like their chemical composition, Global Warming Potential (GWP), and energy efficiency.

Table 1 : Type of refrigerant used in percentage.

R134a	R410a	R22	R32	Ammonia	NA
30.6%	19.5%	5.5%	5.5%	2.7%	36.2%

**LCA Boundaries.** The LCA for 26 out of the 36 studies was carried out from the cradle-to-grave considering the whole cycle from the extraction phase of the raw materials to the disposal phase, whereas the other 10 were performed using the cradle-to-gate approach with a partial assessment that terminates at the gate stage focusing on the upstream stages of production where significant environmental impacts occur. Interestingly, nine out of those ten articles discussed the GSHP or the GHP case, while the tenth one investigated the waste heat-fed heat pump.

**Coefficient of Performance (COP).** 27 studies (75%) presented the Coefficient of Performance (COP) as a significant comparable measure to assess the efficiency of the tested heat pumps at a specific

point in time, in which five of them defined and tested the Seasonal Coefficient of Performance (SCOP) providing a more comprehensive evaluation of its performance over an entire heating season, considering variations in operating conditions and energy use.

**Functional Unit (FU).** A huge difference in the functional units was observed among the literature. 53% of the studies used the thermal energy in Watt-hours (kWh or MWh) as their FU, 11% used the thermal energy in Joules (MJ or GJ), and 19% referred to the lifetime (in years) as their FU.

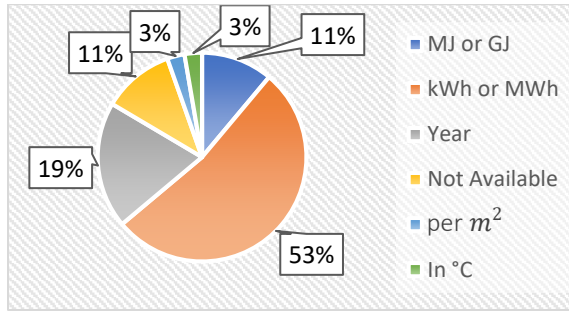


Figure 4: Functional units of heat pump systems (in percentage).

However, 11% of the studies didn't mention their functional unit at all.

Harmonizing the FUs is essential to enable comparable analysis in LCA studies. A unified functional unit ensures consistency and comparability among tested items. This would facilitate benchmarking against best practices to identify areas of improvement and enhance efforts in achieving sustainability goals.

**Life Cycle Impact Assessment (LCIA) method.** The LCIA method is a crucial component of LCA, providing valuable insights into the environmental impacts of HP throughout their entire lifetime. LCIA can be performed through several methods depending on the data availability, goal, and scope of the study (illustrated in Table 2) such as Eco-indicator 99, which serves as both a scientifically grounded method and a practical tool for eco-design ('Sustainable Development', 2012) and which was used by 20% of the articles of this review. The CML method was created by the "Centrum voor Milieukunde Leiden" in the Netherlands in 1992 (Acero et al., 2015) and was used by 14% of the papers as compared to other methods.

Table 2: Life Cycle Impact Assessment methods (LCIA) per type of heat pump.

	CML (1992, 2000, 2001)	ReCiPe (2008, 2016)	EF method 3.0	IMPACT 2002+	(IPCC2001, ELCD, CED, EPS2000 ...)	Eco Indicator (95 and 99)
Geothermal HP	Russo et al., 2014	Pratiwi & Trutnevyte, 2021			Scharrer et al., 2020	
GSHP		Zhang et al., 2022	Famiglietti, Gerevini, et al., 2021	Zhang et al., 2022	Zhang et al., 2022	Koroneos & Nanaki, 2017
		Bonamente & Aquino, 2017				Abusoglu & Sedeeq, 2013
ASHP	Naumann et al., 2022	Sevindik & Spataru, 2022			Zheng et al., 2016 Lozano Miralles et al., 2020	Lozano Miralles et al., 2020
GSHP versus ASHP	Greening & Azapagic, 2012	Marinelli et al., 2020		Violante et al., 2022	Marinelli et al., 2020	
	Sevindik et al., 2021	Aresti et al., 2022 Sevindik et al., 2021				
Systems versus conventional heating methods		Lin et al., 2021	Famiglietti, Toppi, et al., 2021	Khan et al., 2020	Rey Martínez et al., 2011	Khan et al., 2021 Khan et al., 2020
		Riva et al., 2021				

		Famiglietti, Gerevini, et al., 2021		Rey Martínez et al., 2011
Systems versus each other's	(Mahon et al., 2022)	Caduff et al., 2014 Autelitano et al., 2023	Famiglietti et al., 2023	Nitkiewicz & Sekret, 2014
	References with a midpoint	References with endpoint		References with endpoint and midpoint

ReCiPe for the analysis of Environmental Footprints combining Eco-indicator and CML (Acero et al., 2015) was highly used among the tested studies with 36%. Also, IMPACT 2002+ is widely used in academia and industry (Jolliet et al., 2003), and Environmental Footprint (EF) package normalization and weighting was discussed and developed by the Directorate General for the Environment (DG ENV) in 2018 (European Commission. Joint Research Centre., 2018), each method was used by three studies only (accounting for 8%).

Some of these LCIA methods used the endpoint perspective at intermediate stages of cause-effect chains, focusing on specific environmental stressors, such as GHG gas and acidification. However, others employed the endpoint method where evaluation was carried out at the outcomes such as human health or ecosystem quality. Interestingly, some studies chose to use both approaches, the midpoint, and the endpoint. The proposed midpoint-to-endpoint weighting set was primarily intended to draw attention to the relative significance of midpoint indicators with the influence categories they have on endpoints.

### 3. ENVIRONMENTAL IMPACT ASSESSMENT

The performance of domestic HP using LCA was studied over the last two decades in 36 journal articles distinctively in several ways and using different criteria. Some of those studies focused on the effect of refrigerants, other studies focused on the phase that is contributing the most, that is, the usage phase and end-of-life phase of the HP over its lifetime, 75% of the studies presented the COP as a significant indicator for performance evaluation and 64% expressed the FU in terms of thermal energy using different units (kWh, MWh, MJ, or GJ).

According to the seven classifications of heat pump systems presented in this study (Figure 3), environmental impacts such as Global Warming Potential (GWP), Acidification Potential (AP), Eutrophication Potential (EP), and Ozone Depletion were the most reported impact factors, in which some of them were reduced when a conventional system such natural gas furnace, biomass-based, oil-based, bio-oil-based, or condensed gas boilers were replaced by GSHP, GHP, or even in some few cases ASHP. It was concluded in most of the studies that the production and the use phases accounted for the biggest portion of the environmental impact when compared to the other phases (extraction, installation, and end-of-life). Even the most efficient heat pumps equipped with renewable resources discussed by (Autelitano et al., 2023; Famiglietti et al., 2023; Famiglietti, Gerevini, et al., 2021; Famiglietti, Toppi, et al., 2021; Pratiwi & Trutnevyte, 2021; Scharrer et al., 2020; Violante et al., 2022) had a considerable impact on the environment such as Water Use (WU), Land Use (LU) in case of hydropower generation, wind turbine, or solar photovoltaic PV panels.

### 4. LIMITATIONS

Lacking consistency in the methodology (LCIA), form, input of parameters (COP, SCOP, EER, ...), and many others made the comparison of the 36 articles of this review from all aspects impossible. Studying the SCOP of heat pumps is crucial as it provides insights into their overall energy efficiency,



guiding optimization efforts in design, operation, and control strategies. Additionally, understanding SCOP provides informed decisions about system performance and cost-effectiveness when considering heat pump installations.

Dissimilarities in functional units and LCA boundaries led to divergent conclusions about the environmental impact of heat pumps. Moreover, insufficient information was observed about several significant factors such as the geographical area (e.g. climate conditions), the type of refrigerants used, electricity source, electricity mix, and their change over time. In fact, the variation of the electricity mix in a residential building highly affects the LCA outcomes (Bayer et al., 2012) (Pei et al., 2022). By understanding the sources of electricity generation, we can assess environmental footprint, predict energy costs, and inform policies to promote sustainability and energy security. All these factors were not adequately addressed in the LCA studies in which many of them were missing. As consistency and reliability of HPs are achieved on the industrial level through the Environmental Product Declaration (EPD), they can be attained as well on the research level through the development and implementation of a standardized LCA template for HP.

## 5. CONCLUSION

This review suggests that the main methodology for carrying out an LCA for domestic HP in residential buildings needs to be defined in further studies to make a quantitative comparison possible among LCAs of other energy systems such as standardized functional units, typical norms, and measures reflecting the performance of heat pumps and their efficiency such as COP, SCOP, Energy Efficiency Ratio (EER) and LCA system boundaries. A comprehensive methodology for a well-organized LCA for heat pumps should be created and developed that can serve as a practical template for future assessments on heat pumps. This would in turn facilitate well-informed decision-making and sustainable technological advancements in the heating and cooling industry.

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