



**HAL**  
open science

## Potential of air-source heat pumps to reduce environmental impacts in 18 European countries

Célia Masternak, Simon Meunier, Vincent Reinbold, Dirk Saelens, Claude Marchand, Yann Leroy

► **To cite this version:**

Célia Masternak, Simon Meunier, Vincent Reinbold, Dirk Saelens, Claude Marchand, et al.. Potential of air-source heat pumps to reduce environmental impacts in 18 European countries. *Energy*, 2024, 292, pp.130487. 10.1016/j.energy.2024.130487 . hal-04549232

**HAL Id: hal-04549232**

**<https://hal.science/hal-04549232v1>**

Submitted on 24 Feb 2025

**HAL** is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.



Distributed under a Creative Commons Attribution - NonCommercial - NoDerivatives 4.0 International License

# Potential of air-source heat pumps to reduce environmental impacts in 18 European countries

Célia Masternak<sup>1,2</sup>, Simon Meunier<sup>1,2,\*</sup>, Vincent Reinbold<sup>1,2</sup>, Dirk Saelens<sup>3,4</sup>, Claude Marchand<sup>1,2</sup>, Yann Leroy<sup>5</sup>

<sup>1</sup>Université Paris-Saclay, CentraleSupélec, CNRS, GeePs, 91192 Gif-sur-Yvette, France

<sup>2</sup>Sorbonne Université, CNRS, GeePs, 75252 Paris, France

<sup>3</sup>KU Leuven, Department of Civil Engineering, Building Physics and Sustainable Design, Kasteelpark Arenberg 40, BE-3001 Leuven, Belgium

<sup>4</sup>EnergyVille, Thor Park 8310, BE-3600 Genk, Belgium

<sup>5</sup>Laboratoire Génie Industriel, CentraleSupélec, Université Paris-Saclay, 91160 Gif-sur-Yvette, France

\*Corresponding author at: GeePs, 11 Rue Joliot Curie, 91192 Gif-sur-Yvette, France.

E-mail address: simon.meunier@centralesupelec.fr (S. Meunier).

## Abstract:

Air-source heat pumps (ASHP) have a significant potential for decarbonizing the heating sector. In this article, we compare the environmental impacts (climate change, particulate matter formation, human toxicity, and ozone depletion) of an ASHP and a natural gas boiler (NGB). The main originality is that we perform the life-cycle analysis (LCA) of the ASHP and the NGB for 18 European countries while sizing the ASHP according to the dwelling thermal demand. We highlight that using refrigerant R290 instead of R32 decreases the ASHP impact on climate change and ozone depletion. Moreover, the building stock is found to greatly influence the potential benefits of ASHP in several countries (e.g. the Czech Republic, Greece). In recent dwellings, ASHP reduces climate change in 17 out of 18 countries, with a 54% average reduction. However, it often increases particulate matter formation mainly due to the electricity mix, and the use of copper for ASHP manufacturing. Our results can be helpful to European policy makers since they assess in which country ASHP should be installed to yield the highest reduction of environmental impacts. Countrywide, our results can help to deploy ASHP as they indicate which dwelling type should be given priority for ASHP installation.

## Highlights:

- A methodology to perform the LCA of a heat pump and a gas boiler is presented.
- The method is applied to study influential parameters (e.g. building stock).
- Using refrigerant R290 instead of R32 reduces climate change and ozone depletion.
- Important influence of the building stock in countries with high carbon electricity.
- In recent dwellings, heat pumps reduce CO<sub>2</sub> emissions in 17 countries out of 18.

**Keywords:** life-cycle analysis, air-source heat pump, natural gas boiler, decarbonization, environmental impacts

# Nomenclature

## *Abbreviations*

ASHP	Air-source heat pump
COP	Coefficient of performance
DHWT	Domestic hot water tank
GHGE	Greenhouse gases emissions
GSHP	Ground-source heat pump
GWP100	Global warming potential
HTPinf	Human toxicity potential
LCA	Life-cycle analysis
LCI	Life-cycle inventory
NGB	Natural gas boiler
ODPinf	Ozone depletion potential
PMFP	Particulate matter formation potential

## *Parameters*

$c$	Volumetric heat capacity of water (kWh/K.L)
$COP$	Coefficient of performance
$DHL$	Design heat load (kW)
$\Delta T$	Temperature difference between the hot and cold temperatures ( $^{\circ}C$ )
$m$	Heat pump mass (kg)
$Q_{HP,max}$	Heat pump maximal heating capacity (kW)
$Q_{HW}$	Thermal demand for hot water (kWh)
$Q_{nom}$	Heat pump nominal heating capacity (kW)
$T_b$	Base temperature ( $^{\circ}C$ )
$T_e$	Outdoor temperature ( $^{\circ}C$ )
$T_s$	Supply water temperature ( $^{\circ}C$ )
$T_{s,nom}$	Nominal supply water temperature ( $^{\circ}C$ )
$U_{avg}$	Average U-value (W/(m <sup>2</sup> .K))
$V$	Hot water tank volume (L)

# 1 Introduction

## 1.1 Context and literature review

Energy consumption in the building sector accounts for 17.5% of global greenhouse gas emissions (GHGE) [1]. In Europe, 67% of this energy is used for space heating and 13% for water heating [2]. Therefore, the heating sector is a significant contributor to climate change, which has many consequences, such as declining food and water resources, extinction of species, and human health damage [3]. Hence, there is an urgent need for heating decarbonisation. A promising technology for this purpose is the electrically driven heat pump. Indeed, heat pumps have a high (around 3) coefficient of performance (COP, ratio of the thermal energy supplied over the electrical energy consumed). As a result, heat pumps can reduce energy consumption and GHGE compared to conventional heating systems such as natural gas boilers and resistive electric heaters [4] [5]. Following this need for decarbonisation, the number of heat pumps on the market has increased over the past decade: it has increased fivefold between 2011 and 2021 [6]. In 2021, the total number of heat pumps installed in Europe reached 16.98 million [7]. By 2030, the number of heat pumps in the European market is expected to triple [8]. Moreover, with temperatures that will tend to be less extreme in winter, the large-scale implementation of heat pumps will be facilitated especially in cold climates [9]. Other emerging technologies can also help this deployment of heat pumps. Indeed, heat pumps can be included in waste water heat recovery systems [10] or in combined heat and power systems. In this latter situation, heat pumps are coupled to a fuel cell [11], [12], more specifically to a proton exchange membrane fuel cell [13].

Three types of heat pumps are present in the current market: air-source heat pumps (ASHP), water-source heat pumps and ground-source heat pumps (GSHP). However, ASHP are largely prominent in the European market, representing 90% of the sales in 2021 [6]. Despite this growing interest in heat pumps, 46% of the heat in Europe is still provided by natural gas [14]. Since natural gas boilers (NGB) are one of the most widespread systems for residential heating, it is relevant to compare the environmental impacts of ASHP to the ones of NGB. It is also better if the assessment does not only consider climate change but also other environmental impacts such as human toxicity or ozone depletion. Additionally, it is essential to consider the system's entire life cycle [15]. Indeed, considering, for instance, only the GHGE during the use phase might lead to an overestimation of the GHGE reduction reached by installing ASHP since they have higher embodied emissions than NGB due to the refrigerant [16]. Moreover, from one European country to another, many sources of variability may affect the ASHP environmental impacts such as the electricity mix and the building stock. Therefore, those environmental indicators should be quantified for each country separately.

To compute the environmental impacts of a system over its life cycle, life-cycle analysis (LCA) is performed. LCA is a methodology to assess the environmental impacts of a system from raw materials extraction to the management of its end-of-life [17] [18]. Therefore, in this work, we use LCA to assess whether installing ASHP instead of NGB across Europe would be beneficial to reach EU climate targets.

Some articles compared ASHP to competing technologies (e.g. GSHP, NGB or resistive heating). In most articles, the LCA is performed for a single location and a single heat pump size. In the UK, an LCA for air, ground and water source heat pumps was conducted [19] and a hybrid ASHP was compared to an NGB [20]. Moreover, electric heating systems retrofit options (including ASHP) have been compared to gas boilers in the UK using building information modelling [21]. Heat pumps and gas boilers were also studied under several scenarios (circular economy, resource efficiency and limited growth) [22]. In Spain, the replacement of an electric resistive space heating system by an ASHP was studied [23]. In Italy, an ASHP was compared to a GSHP [24] and the environmental impacts of a photovoltaic-driven reversible heat pump were investigated [25]. In Lebanon, an ASHP was compared with solar and conventional electric water heaters [26]. Finally, the comparison between an ASHP and a GSHP in a cold climate (Finland) was performed [16]. For most studies, heat pumps are found to reduce CO<sub>2</sub> emissions and to have several other positive environmental impacts (e.g. reduction of ozone depletion) in comparison to the considered competing technology but, in some cases, they are found to also negatively affect some indicators (e.g. human toxicity and metal depletion).

Johnson [27] considered several heat pump sizes. He performed the LCA of ASHP for typical dwellings (e.g. terraced, semi-detached and detached) in the UK. The author sized the ASHP to match the dwelling's thermal demand (hot water and space heating). Finally, two articles [28] [29] performed the LCA of heat pumps for several countries. Saner et al. [28] conducted the LCA of GSHP for 29 European countries and compared it with conventional heating systems (gas boilers and oil boilers). They found that the highest reduction of GHGE (84%) occurs in Norway. Knobloch et al. [29] quantified the life-cycle CO<sub>2</sub> emissions reduction induced by the use of heat pumps in replacement of fossil boilers for 59 countries worldwide under several scenarios. They pointed out that, in the current situation, heat pumps emit less CO<sub>2</sub> than fossil fuel boilers in 53 countries.

## 1.2 Research gaps, contributions to the research field and article structure

Analysis of the aforementioned literature review allows drawing attention to several aspects that are insufficiently addressed by articles that performed a comparative LCA between a heat pump and another heating system (e.g. NGB or resistive heating) for a single heat pump size and a single country. Even though the country considered usually varies from one study to another, comparing the results of these studies is difficult since they do not consider the same functional unit, system boundary or inventory. In addition, each study performed its LCA for a single heat pump size, although the LCA results strongly depend on it [22], [27]. The influence of heat pump sizing on the LCA was investigated by article [27] but the author did not perform the LCA of another conventional heating system for comparison. Furthermore, the results are obtained for a single location and the author only assessed the impact on climate change.

To our best knowledge, only two articles ([28] and [29]) performed the LCA of heat pumps for several countries. However, [28] did not consider the building stock as a source of variability between countries. The authors used a constant COP (whereas the climate influences it) and considered GSHP while the focus of our article is on ASHP (which represents the majority of the sales in Europe [6]). Moreover, article [29] did not size the heat pump according to the thermal demand of the dwelling and the authors only considered climate change as environmental impact.

On the current European market, 71% of the heat pumps sold in 2019 were equipped with R410a and 28% with R134a [30]. Under the f-gas regulation, the use of these refrigerants is expected to decrease due to their high global warming potential [31]. Maeng et al. [32] studied the LCA of refrigerants with lower global warming potential such as R152a or R1234yf. However, these refrigerants are not currently used for space heating application. Potential interesting refrigerants for space heating are R32 (difluoromethane) or R290 (propane) [33] and R32 is already used by some heat pump manufacturers [30]. To our best knowledge, only articles [24] and [34] considered one of these refrigerants (R32). However study [24] did not include the refrigerant in the LCA and study [34] did not study space heating. Thus, the LCA of an ASHP used for space heating with refrigerant R32 or R290 has not been carried out in previous literature.

In addition, the articles that compared the LCA results of an ASHP to the ones of an NGB did not consider the domestic hot water tank (DHWT) for the NGB. However, there are two possible configurations for the NGB, without a tank (since it can produce hot water instantly) and with a tank.

In this article, we address the scientific gaps arisen from the literature review. The main contribution of this article, in comparison to the existing literature, is the evaluation of the environmental impacts of an ASHP, while sizing it according to the dwelling thermal demand, and of an NGB for 18 European countries. Another contribution consists in performing the LCA of an ASHP equipped with refrigerant R32 and R290. Finally, we compare the LCA of an ASHP to the one of an NGB for two system configurations (with or without a hot water tank for the NGB).

## 1.3 Article overview and structure

In this article, we present a methodology to compare the LCA of an ASHP and of an NGB for 18 European countries. We perform the LCA while sizing the ASHP according to the thermal demand of the considered dwelling. For each country, we consider 4 dwellings based on their construction year. Therefore, we have a different size of ASHP (in kW) and DHWT (in L) for each country and dwelling. To perform the LCA, we need to know the life-cycle inventory (LCI) of these two systems for their specific sizing. For this purpose, we base ourselves on the inventories of reference systems (e.g. 10 kW ASHP) and we consider that the materials of the newly sized system are in the same proportions as those of the reference system [35]. The remainder of this article includes a detailed description of the method in Section 2. In this Section, we detail the LCI of the reference ASHP, NGB and DHWT. We compute the demand for space heating and hot water using the TABULA database [36] with a heat balance. Then, we size the ASHP and DHWT according to these demands. Finally, we explain how we determine the inventory of the sized systems.

The results of the LCA for the NGB and ASHP and for the considered European countries are presented in Section 3. In this Section, we notably investigate which phase of the life-cycle has the strongest influence on the environmental impacts as well as the influence of the refrigerant, the system configuration and the dwelling characteristics on the LCA results. Finally, Section 4 concludes the article.

## 2 Method

In this Section, we present the adopted method to perform the LCA of an ASHP and an NGB for 18 European countries. The method is generic and the databases allow us to provide the results for 18 European countries. However, for the sake of conciseness and clarity, we detail here the input data for solely 4 countries (Belgium, the Czech Republic, Greece and Norway) but similar data are

available for all [36], [37]. Note that these 4 countries have been chosen as illustrative examples because they have very different electricity mix and climate. This can be observed in the following values where we provide the average carbon content of electricity and the average outdoor temperature during the heating season for these 4 countries [36], [38]: Belgium (0.24 kgCO<sub>2</sub>-eq/kWh, 6.2°C), Czech Republic (0.85 kgCO<sub>2</sub>-eq/kWh, 3.8°C), Greece (0.77 kgCO<sub>2</sub>-eq/kWh, 10.1°C) and Norway (0.02 kgCO<sub>2</sub>-eq/kWh, 1.8°C).

The scope of the LCA is from cradle to grave: we consider the extraction, assembly, transport, maintenance, use and end-of-life phases for both heating systems. The following functional unit is considered: heat the indoor air at 20°C and satisfy the hot water demand for the considered dwelling over 20 years. Concerning the boundary conditions, the heating system (ASHP or NGB) is always included. The DHWT is always included with the ASHP. The method offers the possibility to consider two system configurations for the NGB: an NGB equipped with a DHWT and an NGB without DHWT (since the NGB can produce hot water instantly, contrary to the ASHP). The hydraulic circuit, circulating pumps and distribution system (radiators or floor heating) are not included in the LCA. To perform the LCA, we use the Ecoinvent database [38] and the software OpenLCA. The characterization method adopted to calculate the impacts is ReCiPe Midpoint (Hierarchist) [39] [40]. It is a widespread method that previous LCA studies on heat pumps have already used [20], [22], [41].

In Section 2.1, we list the LCI of a reference ASHP, a reference NGB and a reference DHWT. In Section 2.2, we explain how we compute the dwelling thermal demand and how we size the ASHP and DHWT according to the demand of the considered dwelling. We also present how we determine the LCI of the newly sized systems. Finally, in Section 2.3 we present the method for the uncertainty analysis.

## 2.1 Life-cycle inventory

In this Section, we introduce the 10 kW reference ASHP, the 10 kW reference NGB and the 315 L reference DHWT. In Section 2.1.1, we present the LCI for extraction, assembly, transport, maintenance and end-of-life. In Section 2.1.2, we focus on the use phase, more specifically on the efficiencies of the heating systems.

### 2.1.1 Extraction, assembly, transport, maintenance and end-of-life

The LCIs of the 10 kW ASHP, the 10 kW NGB and the 315 L DHWT for the following phases: extraction, assembly, transport, maintenance and end-of-life were compiled and are presented in Table 1. Regarding the amount of refrigerant considered, we use the charging ratios reported in the literature: the charging ratio of R32 is 0.22 kg/kW [42] [43] and the charging ratio of R290 is 0.15 kg/kW [42]. Refrigerants R32 and R290 are not included in the Ecoinvent database [38]. Therefore, LCI of refrigerant were re-built using the work from [44] for R32 and [45] for R290. For transport, we consider that the systems are manufactured in Europe [22]. Therefore, the generic values from Ecoinvent are used [38]. As far as maintenance is concerned, for the ASHP, the refrigerant must be refilled annually due to annual leakage. We consider an annual leakage rate for R32 and R290 of 3.5% [46]. No maintenance is considered for the NGB and the DHWT [19], [47]. Finally, for the end-of-life, we assume the same recycling rates for all countries [41].

Table 1: Reference life-cycle inventories of ASHP, NGB and DHWT for the extraction, assembly, transport, maintenance and end of life phases.

Phase of the life-cycle	Component, energy source or mean of transport	Quantity		
		ASHP	NGB	DHWT
<b>Extraction</b>	Elastomer (tube insulation)	12.6 kg [19]		
	Polyvinylchloride	1.6 kg [19]		
	Lubricating oil	2.7 kg [19]		
	HDPE (high density polyethylene)	0.5 kg [19]	0.9 kg [19]	
	Steel, low alloyed	32 kg [19]	120 kg [19]	83.7 kg [47]
	Reinforcing steel	120 kg [19]		
	Copper	36.6 kg [19]	3.03 kg [19]	0.3 kg [47]
	Refrigerant	R32: 2.2 kg [19], [42], [43] R290: 1.5 kg [19], [42]		
	Brass		0.05 kg [19]	
	Aluminum		7.5 kg [19]	
	Rockwool		8 kg [19]	
	Enamel coating			2.5 kg [47]
	Polyurethane			5.7 kg [47]
Anode			1.3 kg [47]	
<b>Assembly</b>	Electricity (medium voltage)	504 MJ [19]	294 MJ [19]	30 MJ [48]
	Natural gas	37 m <sup>3</sup> [19]	12.5 m <sup>3</sup> [19]	
	Refrigerant leakage during manufacture	3 % [19]		
	Light fuel oil		249 MJ [19]	
<b>Transport</b>	Train	700 km [22]		
	Heavy Truck	300 km [22]		
	Light truck	200 km [22]		
<b>Maintenance</b>	Refrigerant leakage	3.5%/year [46]		
<b>End of life – recycling rates</b>	Copper	61% [22]		
	Steel	75% [22]		
	Plastics	32% [22]		
	Aluminum	69% [22]		
	Refrigerant	80% [22]		
	Rockwool	45% [49]		
	Polyurethane	10% [50]		

### 2.1.2 Efficiency of the heating systems for the use phase

In this article, we compare the environmental impacts of an ASHP with those of an NGB for 18 European countries. For each country, we consider 4 dwellings chosen from the TABULA database according to their construction year (we only considered dwellings built after 1960 because the oldest ones are not isolated enough to install ASHP [51]). To compute the total energy use of each system (electricity for ASHP and natural gas for NGB), we first need the efficiency of the heating systems, as detailed below.

**ASHP.** The coefficient of performance *COP* of the ASHP is the ratio of the thermal power produced by the ASHP over the electrical power it consumes. To compute the *COP*, we use the following equation [52] [53]:

$$COP = (a_0 + a_1 \cdot T_e + a_2 \cdot T_s + a_3 \cdot T_e^2 + a_4 \cdot T_s^2 + a_5 \cdot T_e \cdot T_s) \cdot K \quad (1)$$

with  $T_e$  the outdoor temperature,  $T_s$  the supply water temperature and  $K, a_0, a_1, a_2, a_3, a_4, a_5$  coefficients based on manufacturer data. The coefficients values are gathered in Table 2. The supply water temperature  $T_s$  is usually computed using a heating curve and depends on the heat distribution system (floor heating or radiator) and the dwelling average U-value  $U_{avg}$ , which quantifies the global insulation of the dwelling [54]. In this study, we use the average outdoor temperature during the heating season for  $T_e$  and the supply water temperature is equal to its nominal value  $T_{s,nom}$ , computed according to the following process [54]:

- For floor heating,  $T_{s,nom} = 35^\circ\text{C}$
- For radiators [55], [56]:
  - o If  $U_{avg} > 0.55$ ,  $T_{s,nom} = 55^\circ\text{C}$
  - o If  $0.35 < U_{avg} \leq 0.55$ ,  $T_{s,nom} = 50^\circ\text{C}$
  - o If  $U_{avg} \leq 0.35$ ,  $T_{s,nom} = 45^\circ\text{C}$
- For hot water:  $T_{s,nom} = 60^\circ\text{C}$

We assume that the most recent dwelling is equipped with floor heating and the others are equipped with radiators. Indeed, the market for floor heating is expected to increase in the following years and those heating distribution systems are mostly installed in new dwellings [57]. ASHP coupled to floor heating have a higher  $COP$  than those coupled to radiator, since the nominal supply water temperature  $T_{s,nom}$  is lower [54]. The level of insulation and the climate of the considered country influence the ASHP coefficient of performance. The  $COP$  for the 4 countries are shown in Table 3.

*NGB*. For the *NGB*, we consider a constant efficiency of 95% [58].

## 2.2 Dwellings characteristics and sizing/scaling of the systems

In Section 2.2.1, we detail the space heating and hot water demands for Belgium, the Czech Republic, Greece and Norway. In Section 2.2.2, we explain how the ASHP and DHWT are sized according to the demand of the considered dwelling. Once the systems are sized, we scale, in Section 2.2.3, their inventory (based on the reference inventory of Section 2.1) in order to perform the LCA.

### 2.2.1 Space heating and hot water demands

The space heating demands are based on the TABULA database [36]. This database characterizes the building stock of 18 European countries. To this end, each building stock is described by several archetype dwellings. Dwellings are classified by their construction year. The buildings differ from each other in terms of surface areas and thermal insulations (e.g. U-value of the walls, roof, ...).

For each country, we select 4 detached dwellings from the TABULA database [36] based on their construction year (1961-1990, 1991-2005, 2006-2010 and after 2010). The annual energy demand for space heating  $Q_H$  is computed following the methodology presented in TABULA [59], which is based on the European standard EN ISO 13790:

$$Q_H = Q_{ht} - \eta \cdot (Q_{sol} + Q_{int}) \quad (2)$$

with  $Q_{int}$  the internal heat sources,  $Q_{sol}$  the solar heat load during the heating season,  $\eta$  the gain utilization factor for heating and  $Q_{ht}$  the total heat transfer of the dwelling (heat transfer by transmission and ventilation). The total heat transfer  $Q_{ht}$  is computed using the average outdoor temperature during the heating season, a temperature setpoint of  $20^\circ\text{C}$  and the number of days in the heating season [59].

The hot water demand is based on [37]. It depends on the country and the area of the dwelling. Table 3 gathers the thermal demand (MWh) for space heating and hot water for the 4 countries. Finally, the heating system is considered to perfectly satisfy the thermal demand for space heating and hot water [59]. Using these thermal demands and the efficiency of the heating system (see Section 2.1.2), we compute the electricity or natural gas required during the use phase, which is a key input for performing the LCA.

### 2.2.2 Sizing

For each country and dwelling, the heating system has to be sized according to the dwelling insulation and the climate.

*ASHP*. In this paragraph, we size the ASHP according to the thermal demand of the dwelling. More specifically, we consider the same heat pump product for all dwellings but the heat pumps are sized according to the thermal demand of each dwelling. The maximal thermal power produced by the ASHP  $Q_{HP,max}$  is computed as follows [52]:



$$Q_{HP,max} = b_0 + b_1 \cdot T_e + b_2 \cdot T_s + b_3 \cdot T_s^2 + b_4 \cdot T_e \cdot T_s \cdot \left( \frac{0.8 \cdot DHL}{b_0 + b_1 \cdot T_b + b_2 \cdot T_{s,nom} + b_3 \cdot T_{s,nom}^2 + b_4 \cdot T_b \cdot T_{s,nom}} \right) \quad (3)$$

with  $T_e$  the outdoor temperature;  $T_s$  the supply water temperature;  $b_0, b_1, b_2, b_3$  and  $b_4$  coefficients based on manufacturer data (coefficients values provided in Table 2);  $DHL$  the dwelling design heat load;  $T_b$  the base temperature and  $T_{s,nom}$  the nominal supply temperature. The  $DHL$  is computed using norm EN 12831. It corresponds to the thermal losses of the dwelling (by transmission and ventilation) computed at the base temperature  $T_b$  (lowest temperature recorded for at least five days). The base temperatures for each country are based on ASHRAE's database [60]. The heating system must be able to supply at least 80% of the  $DHL$ . Finally, the nominal supply temperature  $T_{s,nom}$  is computed according to the process described in Section 2.1.2.

Table 2: Coefficients for the computation of the COP and of the maximal thermal power produced by the ASHP  $Q_{HP,max}$

COP		$Q_{HP,max}$	
$a_0$	8.24	$b_0$	9.35
$a_1$	$1.58 \times 10^{-1}$	$b_1$	$3.19 \times 10^{-1}$
$a_2$	$-1.95 \times 10^{-1}$	$b_2$	$-6.13 \times 10^{-2}$
$a_3$	$1.01 \times 10^{-3}$	$b_3$	$4.44 \times 10^{-3}$
$a_4$	$1.48 \times 10^{-3}$	$b_4$	$2.45 \times 10^{-3}$
$a_5$	$-2.33 \times 10^{-3}$		
$K$	1.19		

The heat pump nominal heating capacity  $Q_{nom}$  is given at  $T_e = 2^\circ\text{C}$  and  $T_s = 35^\circ\text{C}$  [19]:

$$Q_{nom} = Q_{HP,max}(2^\circ\text{C}, 35^\circ\text{C}) \quad (4)$$

From the heat pump nominal heating capacity  $Q_{nom}$ , its mass  $m$  is computed as following [35]:

$$\log(m) = 1.7 + 0.67 \cdot \log(Q_{nom}) \quad (5)$$

The ASHP heating capacity and its corresponding mass for Belgium, the Czech Republic, Greece and Norway are listed in Table 3.

*DHWT*. We size the DHWT according to the daily thermal power required for hot water  $Q_{HW}$  (kWh):

$$V = \frac{Q_{HW}}{c \cdot \Delta T} \quad (6)$$

with  $V$  the tank volume,  $c$  the volumetric heat capacity of water (kWh/K.L),  $\Delta T$  the temperature difference between the hot and cold temperatures. The volumes for each country are summarized in Table 3.

*NGB*. In this study, we consider a fixed NGB size for all the countries and dwellings: a 30 kW NGB weighing 37 kg [61]. Indeed, this NGB heating capacity is sufficient to satisfy the building thermal losses at base temperature and to provide hot water. Considering a fixed size might slightly oversize the NGB for some countries (e.g. France). However, the heating capacity has little influence on the materials required for NGB manufacturing [41].

Table 3: Climate, thermal demands for space heating and hot water, systems sizing and ASHP COP for 4 TABULA archetype dwellings of 4 countries

Country Average outdoor temperature $T_e$ [36] and base temperature $T_b$ [60]	TABULA dwelling reference, construction year and age category. <i>Notation: [TABULA dwelling reference] ([construction year]); [age category]</i>	Demand for space heating (MWh/year) [36] and hot water (MWh/year) [37] <i>Notation: [value for space heating]; [value for hot water]</i>	ASHP heating capacity (kW) and mass (kg) <i>Notation: [value for heating capacity]; [value for mass]</i>	DHWT volume (L)	ASHP COP for space heating and for hot water <i>Notation: [value for space heating]; [value for hot water]</i>
Belgium $T_e = 6.2^\circ\text{C}$ $T_b = -5^\circ\text{C}$	BE.N.SFH.06.Gen (>2012); most recent	20.4 MWh/year; 6.4 MWh/year	17.4 kW; 340 kg	340 L	4.4; 2.4
	BE.N.SFH.05.Gen (2006-2011); recent	26.0 MWh/year; 6.4 MWh/year	28.2 kW; 470 kg	340 L	2.6; 2.4
	BE.N.SFH.04.Gen (1991-2005); mid	33.5 MWh/year; 6.1 MWh/year	33.6 kW; 528 kg	330 L	2.6; 2.4
	BE.N.SFH.03.Gen (1971-1990); old	37.5 MWh/year; 5.6 MWh/year	36.4 kW; 557 kg	300 L	2.6; 2.4
Czech Republic $T_e = 3.8^\circ\text{C}$ $T_b = -10.6^\circ\text{C}$	CZ.N.SFH.07.Gen (>2011); most recent	12.3 MWh/year; 4.3 MWh/year	16.1 kW; 322 kg	230 L	4.2; 2.3
	CZ.N.SFH.06.Gen (1995-2010); recent	15.9 MWh/year; 3.1 MWh/year	28.1 kW; 468 kg	170 L	2.8; 2.3
	CZ.N.SFH.05.Gen (1981-1994); mid	25.5 MWh/year; 3.2 MWh/year	55.3 kW; 738 kg	170 L	2.5; 2.3
	CZ.N.SFH.04.Gen (1961-1980); old	37.8 MWh/year; 4.3 MWh/year	81.5 kW; 956 kg	230 L	2.5; 2.3
Greece $T_e = 10.1^\circ\text{C}$ $T_b = 2.8^\circ\text{C}$	GR.ZoneB.SFH.04.Gen (>2011); most recent	7.6 MWh/year; 4.7 MWh/year	9.9 kW; 232 kg	250 L	4.9; 2.6
	GR.ZoneB.SFH.03.Gen (2001-2010); recent	8.0 MWh/year; 2.1 MWh/year	9.1 kW; 220 kg	110 L	2.8; 2.6
	GR.ZoneB.SFH.02.Gen (1981-2000); mid	21.4 MWh/year; 5.4 MWh/year	23.9 kW; 420 kg	290 L	2.8; 2.6
	GR.ZoneB.SFH.01.Gen (<1980); old	21.4 MWh/year; 3.0 MWh/year	21.4 kW; 390 kg	160 L	2.8; 2.3
Norway $T_e = 1.8^\circ\text{C}$ $T_b = -11.7^\circ\text{C}$	NO.N.SFH.07.Gen (>2011); most recent	17.6 MWh/year; 4.2 MWh/year	18.9 kW; 359 kg	220 L	4.0; 2.3
	NO.N.SFH.06.Gen (2001-2010); recent	23.4 MWh/year; 7.3 MWh/year	39.2 kW; 585 kg	400 L	3.0; 2.3
	NO.N.SFH.05.Gen (1991-2000); mid	22.7 MWh/year; 3.6 MWh/year	31.6 kW; 506 kg	190 L	3.0; 2.3
	NO.N.SFH.03.Gen (1968-1974); old	25.1 MWh/year; 3.5 MWh/year	42.7 kW; 620 kg	190 L	2.7; 2.3

### 2.2.3 Scaling

In Section 2.2.2, we explained how to size the systems (ASHP and DHWT) according to the thermal demand of the dwelling. To perform the LCA, we need to know the quantity of materials and energy used in the different phases of the LCA (extraction, assembly, transportation, maintenance and end-of-life). To this end, we use the reference ASHP and DHWT introduced in Section 2.1. Based on [35], in order to determine the amount of materials and energy in ASHP and DHWT of different sizes, we

use the values of the reference ASHP and DHWT and consider that the components of the ASHP and DHWT remain in the same proportions as in the reference systems. The only exception is for the refrigerants since we use the charging ratios.

To briefly summarize the overall method presented in this Section 2: with the sizes of the systems and their reference inventory (see Table 1), we deduce the final life-cycle inventory for extraction, assembly, transport and end of life. The final life-cycle inventory for operation is determined with the thermal demand of the dwelling and the efficiency of the heating system. For the ASHP, the final life-cycle inventory for maintenance is determined with the ASHP heating capacity and the refrigerant charging ratio. In Figure 1, we illustrate the overall method to perform the life-cycle analysis of a dwelling equipped with an ASHP and a DHWT (from the country and building characteristics to the environmental impact categories including the sizing of the systems).

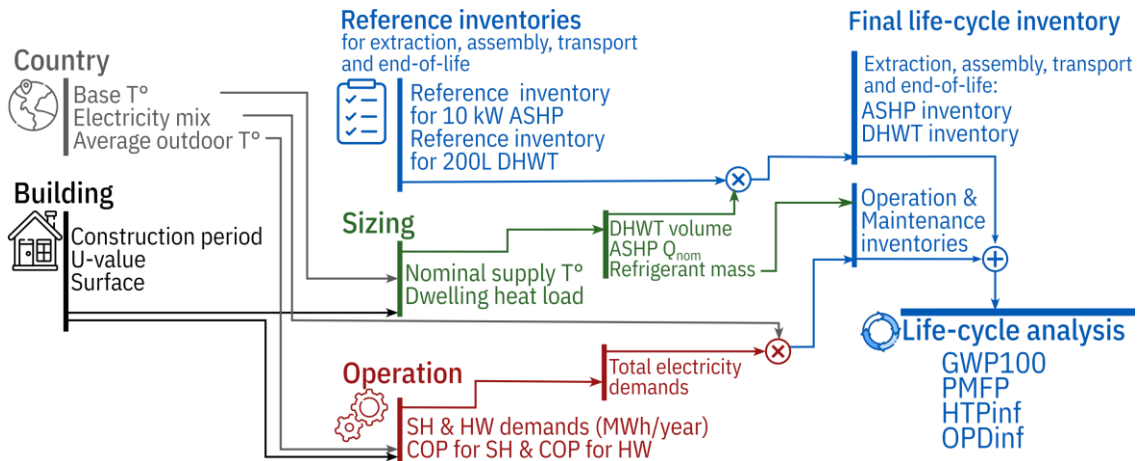


Figure 1: Synoptic diagram providing an overview of the method to perform the LCA of a dwelling equipped with an ASHP and a DHWT. ASHP: air-source heat pump; COP: coefficient of performance; DHWT: domestic hot water tank; HW: hot water;  $Q_{nom}$ : ASHP nominal heating capacity, SH: space heating.

### 2.3 Uncertainty analysis

We perform an uncertainty analysis to assess the robustness of our results, using the dedicated functionality of OpenLCA. We set a lognormal distribution for each input parameter [16], [41]. The uncertainty factors (i.e. standard deviation of the distribution) and the supporting references are gathered in Table 4. The mean of each distribution is set equal to the value in the final life-cycle inventory. The uncertainties are propagated with Monte-Carlo simulations. We perform 2000 simulations [41].

Table 4: Uncertainty factors used to perform the uncertainty analysis

	Uncertainty factor
Construction material	1.1 [41]
Energy needed for assembly	1.1 [62]
Transport	1.5 [16]
Recycling rates	1.5 [16]
Refrigerant leakage	Manufacture: 1.1 [41] Maintenance : 1.2 [63] [64]
Refrigerant charging ratio	1.2 [16]
Thermal energy during use phase	1.1 [41]

## 3 Results

We present the results for the following impact categories [28], [46], [65]:

- *GWP100*. With the ReCiPe midpoint Hierarchist method, GWP100 (i.e., global warming potential) is the impact category for climate change; the time horizon is 100 years [66]. Climate change (kg CO<sub>2</sub>-eq) is the change in global temperature caused by the release of GHGE due to human activities. The rise in temperature is expected to cause decline in food and

water resources, extinction of species, and human health damage [3]. Reducing GHGE is a very important motivation for the large-scale implementation of heat pumps [29], [67] thus explaining why this impact category was selected.

- *PMFP*. Particulate matter formation (kg PM10-eq) represents suspended particles mostly due to combustion (for instance, coal combustion to produce electricity). They can cause health problems, especially in the respiratory system [68]. PMFP is an indicator of interest when studying systems working with electricity [28], [65].
- *HTPinf*. Human toxicity (kg 1,4DCB-eq) – It quantifies the toxic effect of chemicals on humans (potential harm of a unit of chemical released into the environment). In particular, for the considered case, it is mainly caused by electricity production from coal [68] but also by copper manufacturing [28].
- *ODPinf*. Ozone depletion (kg CFC-11-eq) quantifies gases that cause damage to the ozone layer. Therefore, more ultraviolet radiations reach the Earth's surface, which can be harmful to health. In particular, chlorofluorocarbon and hydrofluorocarbon refrigerants (such as R134a) can cause it [68], [69], making it an important impact category to follow when heat pumps are considered.

In addition, as certain readers may be interested by other impact categories, we provided results for all impact categories of the ReCipe midpoint Hierarchist method in an Excel Table in the Supplementary information.

In this Section, we compare LCA results for ASHP and NGB. In Section 3.1, a detailed comparison is performed for a Belgian dwelling in the age category 'most recent' (see Table 3) to assess the influence of the different phases of the LCA. In Section 3.2, we study the impact of the refrigerant, the system configuration and the dwelling on the LCA results for Belgium, the Czech Republic, Greece and Norway. In Section 3.3, we compare the LCA results for 18 European countries. Note that, except mentioned otherwise (e.g. when the specific analysis on the influence of the refrigerant is carried out), we present the results for the most recent dwelling, for refrigerant R32 in the ASHP (which is more common than R290 at the moment [30]) as well as for the ASHP and the NGB both coupled to a DHWT. Moreover, we include the results of the uncertainty analysis in the Figures presented below using box plots. Each box extends from the 1<sup>st</sup> and 3<sup>rd</sup> quartiles with a line at the median. The top whisker indicates 95<sup>th</sup> percentile and the bottom one indicates the 5<sup>th</sup> percentile.

### 3.1 Detailed results for a case study

In this Section, we consider a Belgian dwelling in the age category 'most recent'.

#### 3.1.1 Results for four impact categories

In Figure 2, we plot the results of the LCA for the ASHP (plain) and the NGB (hatched) for the impact categories detailed above. We notice that, for the considered case, the ASHP reduces the environmental impact for 3 out of 4 impact categories. In particular, the global warming potential (GWP100) is divided by ~3.5. The decrease in GWP100 is notably due to the high *COP* of the ASHP (4.4 for space heating and 2.4 for hot water in this case). The impact on particulate matter formation (PMFP) is similar for ASHP and NGB. Belgian electricity emits more particles than natural gas (around 3 times more) but this is compensated by the high *COP*. The ASHP increases human toxicity (HTPinf): it is twice higher than with an NGB. This difference is due to the Belgian electricity mix, which is around ten times worse than natural gas in terms of human toxicity. Moreover, the ASHP requires more copper than the NGB, which is also responsible for human toxicity. ASHP reduces the impact on ozone depletion (ODPinf). This is notably related to the fact that refrigerant R32 has a smaller influence on ozone depletion compared to other refrigerants (e.g. R134a) [69].

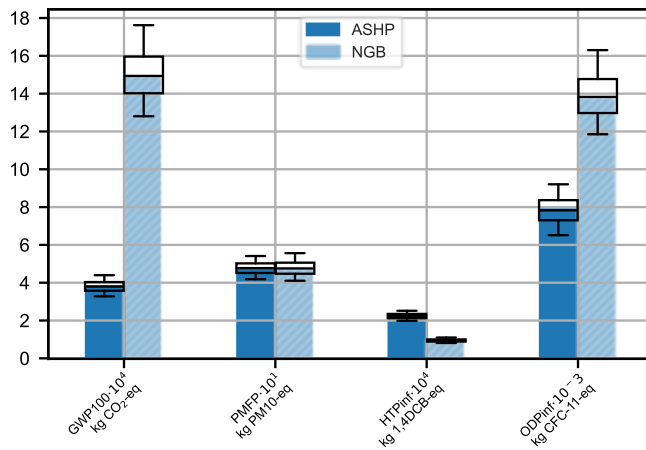


Figure 2: Comparative LCA for 4 impact categories between an ASHP and an NGB for a 'most recent' Belgian dwelling.

### 3.1.2 Results per phase of the life-cycle

In Figure 3, we assess the contribution of each phase of the life-cycle to the environmental impacts. The results presented in the previous Section are normalized. We notice that, for the NGB, the use phase is the main contributor (at least 95%) to the four impact categories and that the manufacturing phase has little influence. Indeed, the NGB only requires a few materials for its manufacture, which explains why the manufacturing phase is not predominant. For the ASHP, the use phase also has the most influence but the contribution of the manufacturing is more significant (~20-25% for the impact categories particulate matter formation (PMFP) and human toxicity (HTPinf)). This is mainly due to the important quantity of copper used for the manufacturing. Due to refrigerant leakage, the maintenance phase contributes to 6% of climate change (GWP100) and ozone depletion (ODPinf). Therefore, reducing the refrigerant leakage would lower the impact of the ASHP on climate change and ozone depletion. For both systems, the transport has almost no impact. We notice that the recycling of refrigerant positively impacts ozone depletion. Results for the different stages for other dwellings and countries were added in an Excel file placed in supplementary material. Overall, the trends highlighted in this Section are consistent with the findings for the other cases studied.

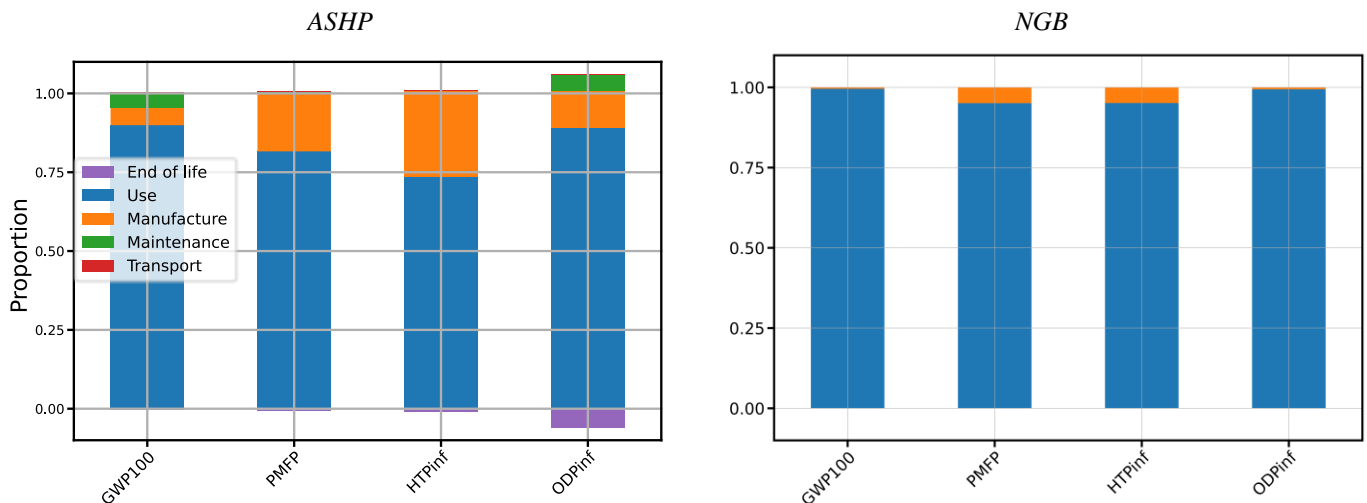


Figure 3: Contribution of each phase on the LCA for a 'most recent' Belgian dwelling equipped with an ASHP or an NGB.

## 3.2 Influence of different parameters on the LCA

As presented in the first paragraph of Section 2, we here detail the results for 4 European countries which differ in their climate and electricity mix.

### 3.2.1 Influence of the refrigerant

In this Section, we consider that the same ASHP can be used with refrigerant R32 or R290 [70]. In Figure 4, we plot the LCA results for an ASHP equipped with refrigerant R32 (ASHP R32), an AHSP equipped with refrigerant R290 (ASHP R290) and an NGB. Overall, results indicate that the influence of the refrigerant is low compared to the total impact. More specifically, we notice that

the refrigerant change does not impact particulate matter formation (PMFP) and human toxicity (HTPinf), which is coherent with the results presented in Section 3.1.2. Indeed, we have seen that the refrigerant mostly influences climate change (GWP100) and ozone depletion (ODPinf), through its leakage. Figure 4 shows that using R290 instead of R32 tends to decrease the impact on climate change and ozone depletion for the 4 countries. Concerning ODPinf, the relative decrease is more important in the Czech Republic and Norway. We also notably notice that the benefits of using R290 instead of R32 are small in Greece because the size of the ASHP is relatively low compared to the other countries (10 kW for Greece and around 20 kW for the other countries). Therefore, using refrigerant R290 should be particularly encouraged in dwellings requiring a high-capacity heat pump.

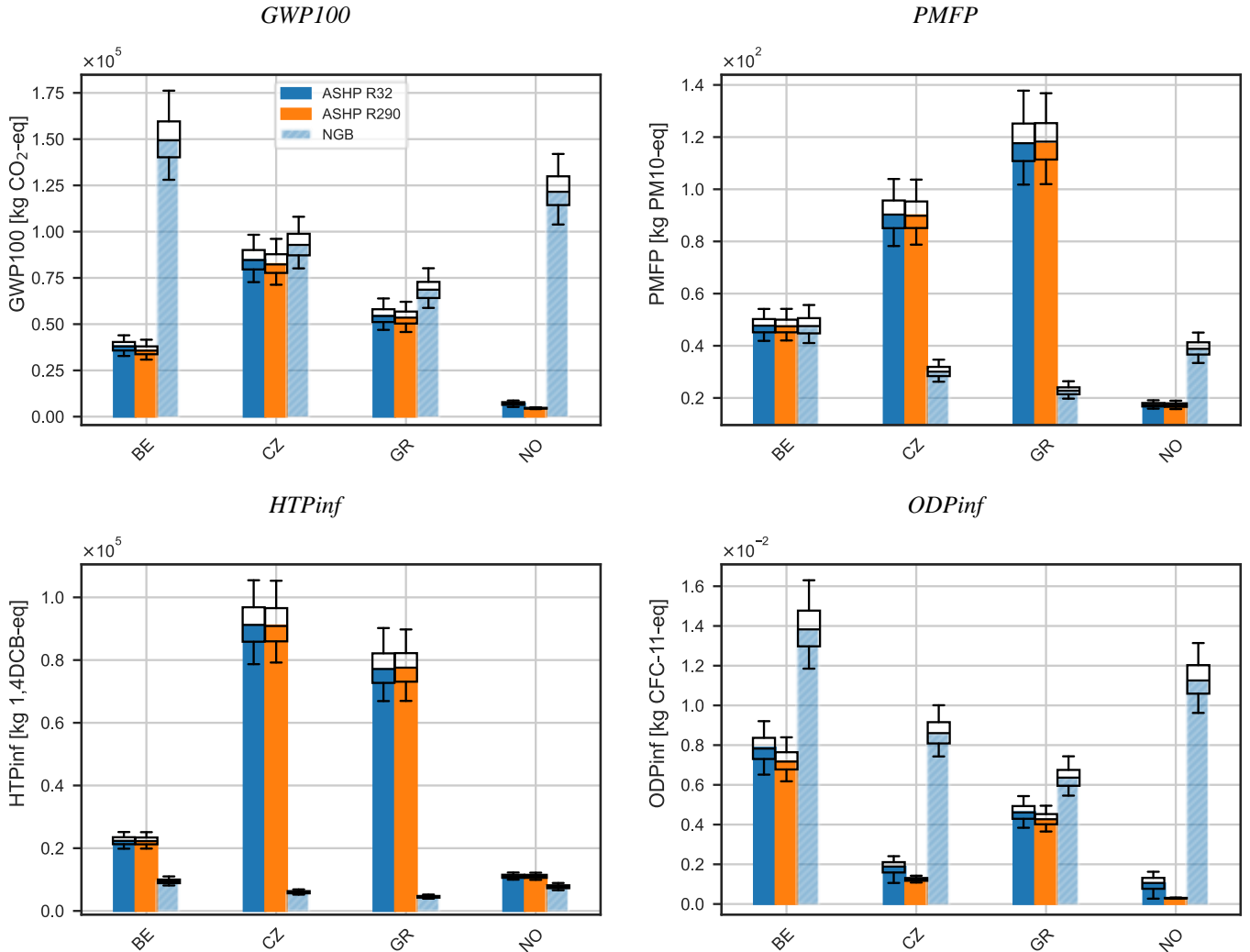


Figure 4: Influence of the ASHP refrigerant (R32 or R290) on the LCA results for 4 countries and for 4 impact categories.

### 3.2.2 Influence of the system configuration

In this Section, we investigate the impact of including the DHWT in the LCA of the NGB. In Figure 5, we plot the LCA results for 3 systems: ASHP with DHWT, NGB with DHWT and NGB without DHWT. We notice that the DHWT has very little contribution on the environmental impact categories. Considering or not the DHWT in the LCA of the NGB does not change the trend of the results for the 4 countries considered. This is because at least 95% of the impact of the NGB is due to the use phase (see Section 3.1). The impact of the DHWT can slightly be seen on particulate matter formation (PMFP), because the manufacturing of metals emits particulate matters. Therefore, all in all, it may be beneficial to install DHWT with NGB since it increases the flexibility of the dwelling [71].

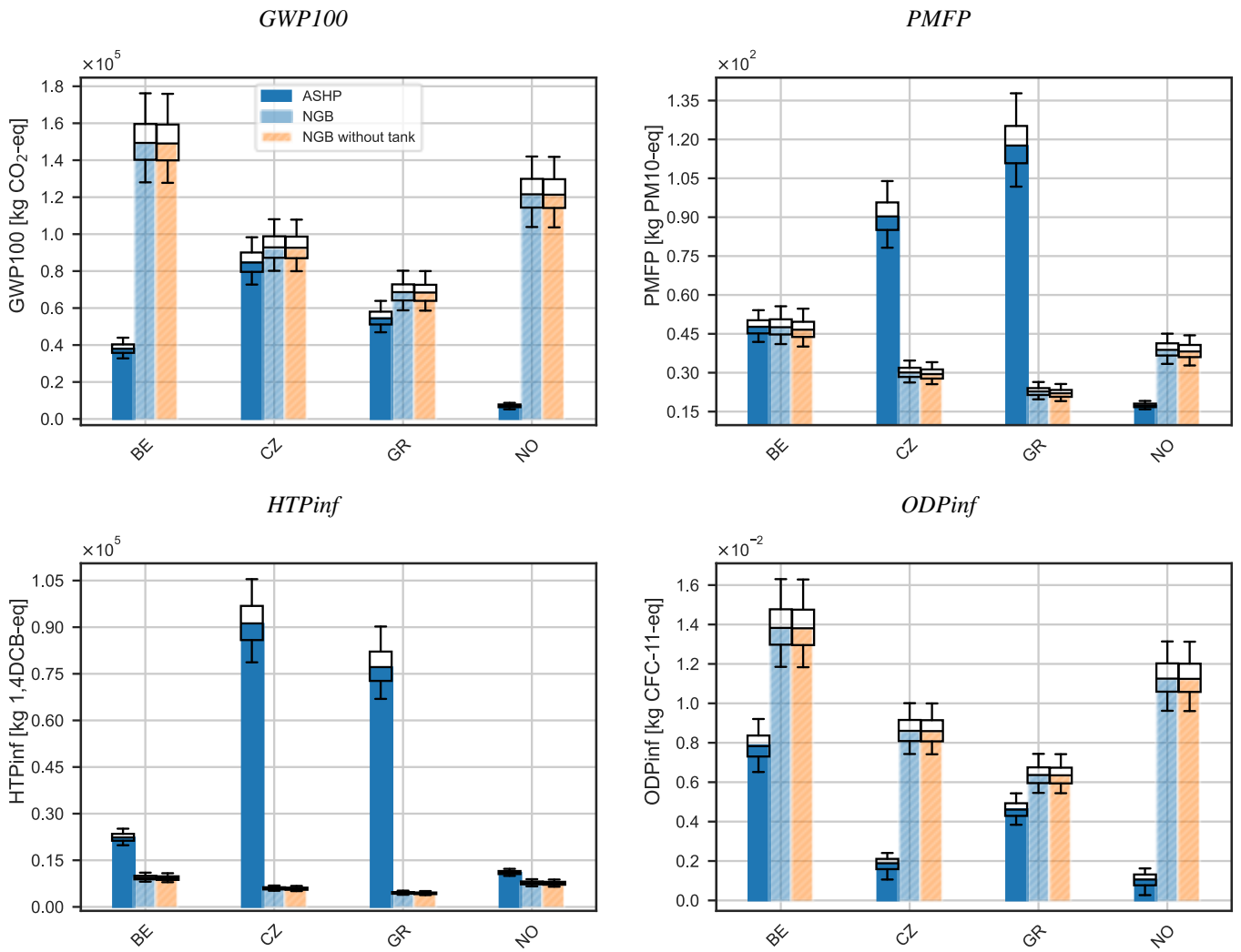


Figure 5: Influence of the system configuration (NGB or NGB coupled to DHWT) on the LCA results for 4 countries and for 4 impact categories.

### 3.2.3 Influence of the dwelling

In this Section, we assess the influence of the dwelling construction year on the comparative LCA. In Figure 6, we plot results of the environmental impacts of the ASHP and NGB for 4 European countries and for 4 dwelling types per country. The dwelling characteristics are detailed in Table 3. We highlight the following key results from Figure 6:

- For most recent dwellings, installing an ASHP instead of an NGB tends to allow a reduction of climate change (GWP100) in the 4 considered countries. The reduction is particularly high in Norway, where climate change is divided by 18 for the most recent dwelling. This reduction is due to the low carbon content of electricity. However, in the Czech Republic and in Greece, for the 3 oldest dwellings, the installation of ASHP tends to slightly increase the impact on climate change (with a maximum increase of ~30% for the oldest dwelling in the Czech Republic).
- The ASHP worsens the environmental impact compared to the NGB for human toxicity (HTPinf) in the 4 countries, regardless of the dwelling considered. Human toxicity is notably due to lignite combustion [65], [72]. Hence, electricity mixes based on fossil fuels tend to have higher human toxicity than natural gas. Moreover, copper is the main contributor to human toxicity in the manufacturing phase (which accounts for around 30% of the total impact). ASHP requires more copper than NGB, which also explains the increased human toxicity.
- More recent dwellings do not necessarily lead to lower environmental impacts due to higher surfaces. For instance, in Norway, dwellings built in 2001-2010 have higher environmental impacts than those built in 1991-2000. Therefore, it is necessary to consider a detailed description (e.g. accounting for the U-values and surfaces) of the dwelling in order to determine the environmental impacts of a heating system: the construction year alone is not a sufficient indicator.

- Results are not favorable to ASHP for old dwellings in the Czech Republic when considering climate change (GWP100), particulate matter formation (PMFP) and human toxicity (HTPinf). Indeed, these dwellings require high capacity ASHP (>80 kW), and the lower COP (due to the cold climate) leads to a higher need for electricity. Moreover, the electricity mix of the Czech Republic is mostly based on fossil fuels.
- ASHP tends to reduce the impact on ozone depletion (ODPinf), no matter the dwelling. For the ASHP, an important source of ozone depletion (not in the use phase) is the refrigerant R32 (during manufacture and maintenance). An interesting result is that the charging factor of refrigerant R32 and its annual leakage rate are low enough to prevent the ASHP from increasing ozone depletion compared to NGB.

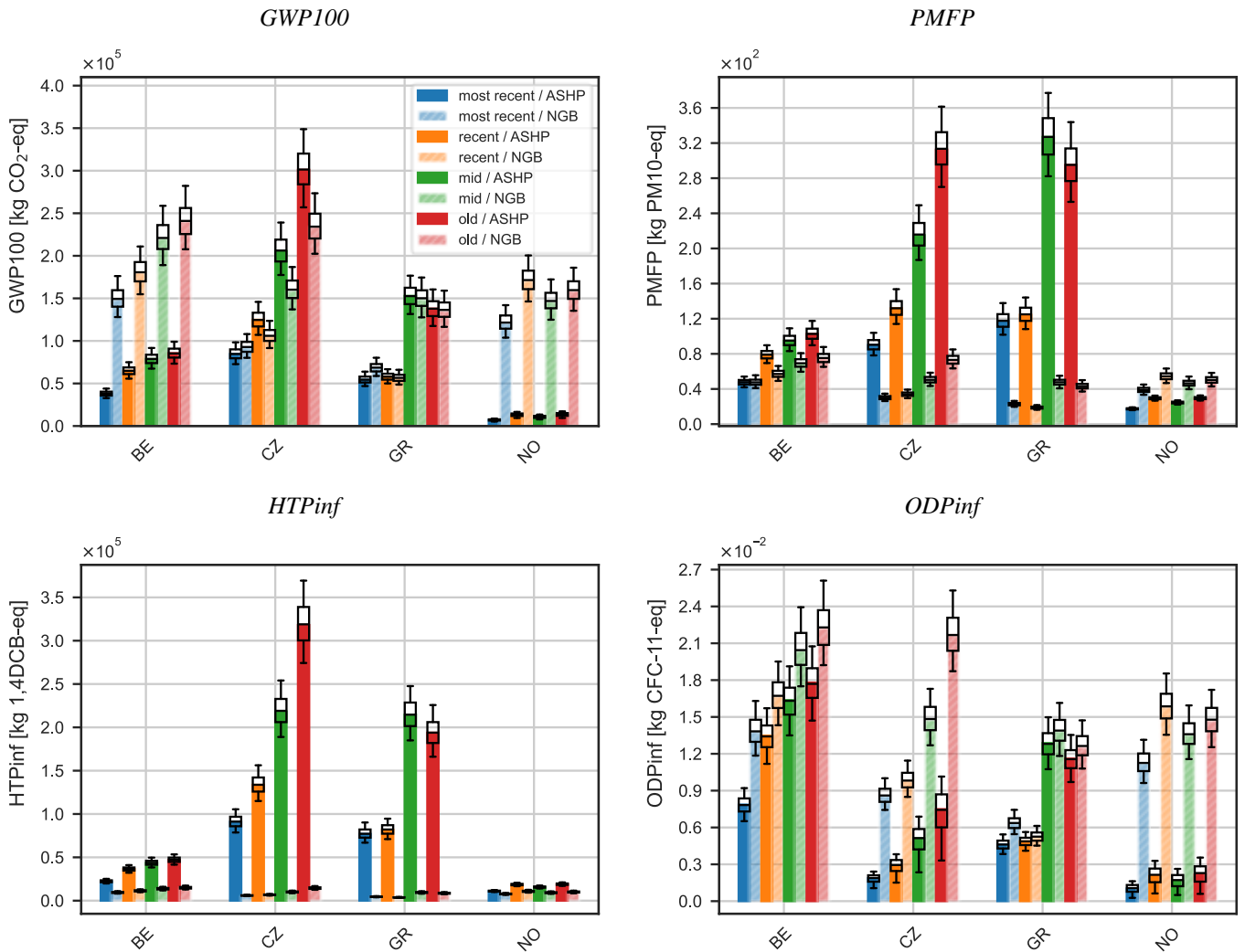


Figure 6: Influence of the dwelling age category on the LCA results for 4 countries and for 4 impact categories.  
 Note: plain bars correspond to ASHP and hatched bars correspond to NGB

### 3.3 Influence of the country

In this Section, we investigate the influence of the country on the potential of ASHP to reduce environmental impacts compared to NGB. We perform the results for each country's most recent and oldest dwelling. In Figure 7, we plot the relative difference between the ASHP and the NGB for climate change (GWP100) and particulate matter formation (PMFP) for 18 European countries. When the value is negative (in green), the ASHP reduces the environmental impact compared to the NGB. *GWP100*. For the most recent dwellings, ASHP allows a reduction of climate change (GWP100) in 17 countries out of 18 (climate change is increased in Poland). Even in countries with a high-carbon electricity mix (such as the Czech Republic or Greece), installing ASHP in recent dwellings reduces climate change. Climate change reduction is similar (~90%) in France, Norway and Sweden, whereas the demand in Norway and Sweden is three times higher, and the ASHP size is five times higher than in France due to the colder climate. The lower carbon content of electricity in Norway and Sweden compensates for their colder climate (which is responsible for a lower COP compared to France, where the climate is warmer). For older dwellings, ASHP allows a reduction of climate change (GWP100) in 15 countries



out of 18. We still have a ~90% reduction for France, Norway and Sweden. However, in the Czech Republic and in Greece, we have a reduction of climate change in most recent dwellings and an increase in old dwellings. In old Czech, Greek and Polish dwellings, for ASHP to be environmentally beneficial, it is necessary to decarbonize the electricity mix.

*PMFP.* For the most recent dwellings, ASHP allows a reduction of the particulate matter formation (PMFP) in 4 countries out of 18. The maximum reduction is 55% in Norway. However, we notice an increase of 410% in Greece and in Slovenia and of 470% in Poland. For older dwellings, ASHP allows a reduction of the particulate matter formation (PMFP) in 3 countries out of 18. The increase is the most important in Poland (750% increase). In Belgium, ASHP increases PMFP in old dwellings but reduces it in most recent dwellings. For the ASHP, in the manufacturing phase, PMFP is mainly (70%) due to the use of copper. In the use phase (which accounts for ~75% of the total impact), PMFP is particularly high if the electricity mix includes lignite combustion [65]. Therefore, the increase due to ASHP is noteworthy in Greece, Poland and Slovenia because the electricity mix relies on lignite combustion. However, it is important to note that European decarbonization plans, which notably aim at shifting out fossil fuels, will decrease the impact of ASHP on PMFP [73].

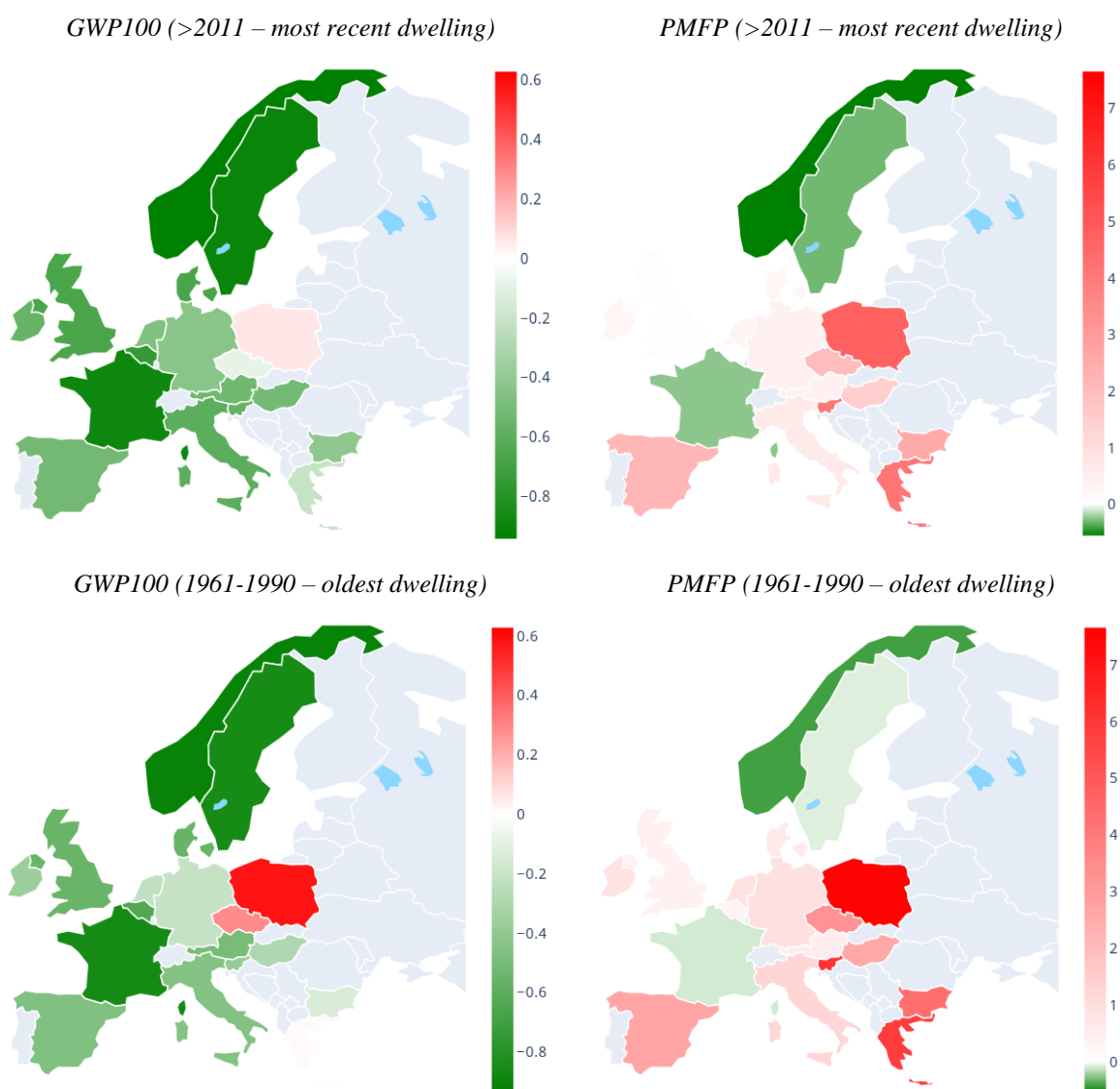


Figure 7: Relative difference between an ASHP and an NGB for 18 European countries for climate change (GWP100) and particulate matter formation (PMFP)

Note: Negative values (green) mean that ASHP improves the environmental impact

The maps for all 4 indicators (including HTPinf and ODPinf) and all dwellings (including dwellings built between 1990 and 2011) can be found in the supplementary HTML file *Europe\_map.html*. This file is accessible through a downloadable .rar file placed in the supplementary materials.

## 4 Conclusion

The main advance of this article with respect to the current state of the art lies in assessing the environmental impacts of an air source heat pump (ASHP), while sizing it to match the thermal requirements of the dwelling, and of a natural gas boiler (NGB) across 18 European countries. Additional contributions encompass conducting a life-cycle assessment (LCA) for an ASHP using refrigerants R32 or R290, as well as comparing the LCA results of an ASHP with those of an NGB under two system configurations (with or without a hot water tank for the NGB). Furthermore, the article quantifies the impact of dwellings' construction year on several environmental impact categories.

Results indicate that the use phase has the most influence on the environmental impacts for both the ASHP and the NGB and that the manufacturing phase is the second biggest contributor (up to 25%). The choice of the ASHP refrigerant influences climate change and ozone depletion. In particular, our results indicate that using refrigerant R290 instead of R32 tends to slightly reduce climate change and ozone depletion, notably for high capacity ASHP. Overall, when comparing the impacts of the ASHP and of the NGB on ozone depletion, it appears that, no matter if the R32 or the R290 refrigerant is used, the ASHP contributes less to ozone depletion than the NGB. This is notably due to the low charging factors and annual leakage rates of these refrigerants. We also highlight that considering or not the hot water tank in the LCA of the NGB has very little impact on the results. We found that, in recent dwellings, ASHP allows for climate change reduction in 17 out of 18 countries with an average reduction of 54%. For old dwellings, the average reduction is 37%. Regarding particulate matter formation, ASHP allows for a reduction in only 4 countries out of 18 for new dwellings and in 3 countries for old dwellings. However, shifting out from fossil sources (e.g. lignite) in electricity mixes will positively impact the environmental impacts of ASHP on particulate matter formation, climate change and human toxicity. Therefore, in Europe, it seems relevant to encourage these initiatives with additional funding. Our proposed methodology and results can notably be helpful to academics, investors and policy makers. In particular, Europe-wide, our results allow to assess in which country it would be particularly beneficial to install ASHP (e.g. France, Norway and Sweden) and to quantify the potential associated changes in the environmental impacts. At the national scale, our work can help to identify in which type of dwelling the installation of ASHP is the most relevant.

Finally, this work could be pursued by coupling the environmental life-cycle analysis to a life-cycle cost analysis to identify areas where ASHP could yield the most positive environmental impacts at the lowest cost. Another relevant future research could be to compare the environmental impacts of ASHP with those of other heating systems (e.g., district heating, solar heating systems), depending on the area. It would also be interesting to study in detail the environmental impacts of emerging ASHP applications (e.g., combined heat and power systems featuring a fuel cell).

## CRediT authorship contribution statement

**Célia Masternak:** Conceptualization, Methodology, Software, Validation, Resources, Writing – Original Draft, Writing – Review & Editing, Visualization, Project administration

**Simon Meunier:** Conceptualization, Methodology, Validation, Resources, Writing – Review & Editing, Supervision, Visualization, Project administration, Funding acquisition

**Vincent Reinbold:** Conceptualization, Methodology, Software, Validation, Resources, Writing – Review & Editing, Supervision, Visualization, Project administration, Funding acquisition

**Dirk Saelens:** Conceptualization, Methodology, Validation, Resources, Writing – Review & Editing, Supervision, Project administration

**Claude Marchand:** Conceptualization, Methodology, Validation, Resources, Writing – Review & Editing, Supervision, Project administration, Funding acquisition

**Yann Leroy:** Conceptualization, Methodology, Software, Validation, Resources, Writing – Review & Editing, Supervision

## Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

## Acknowledgment

The authors would like to thank the reviewers for their comments and suggestions which allowed to improve the article.

## References

- [1] C. Delmastro, “Buildings, sectoral overview (IEA)”, Sept. 2022, URL: <https://www.iea.org/reports/buildings>, [Accessed: 17-July-23].
- [2] European Commission, “REPowerEU Plan, EU external energy management in a changing world”, May 2022, URL: <https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=JOIN%3A2022%3A23%3AFIN&qid=1653033264976>, [Accessed: 17-July-23].
- [3] IPCC, “Synthesis report of the IPCC sixth assessment report (AR6)”, Mar. 2023, URL: [https://report.ipcc.ch/ar6syr/pdf/IPCC\\_AR6\\_SYR\\_LongerReport.pdf](https://report.ipcc.ch/ar6syr/pdf/IPCC_AR6_SYR_LongerReport.pdf), [Accessed: 17-July-23].
- [4] H. Zhang, L. Zhou, X. Huang, and X. Zhang, “Decarbonizing a large City’s heating system using heat pumps: A case study of Beijing”, *Energy*, vol. 186: 115820, Nov. 2019, doi: 10.1016/j.energy.2019.07.150.
- [5] G. Ala, A. Orioli, and A. Di Gangi, “Energy and economic analysis of air-to-air heat pumps as an alternative to domestic gas boiler heating systems in the South of Italy”, *Energy*, vol. 173, pp. 59–74, Apr. 2019, doi: 10.1016/j.energy.2019.02.011.
- [6] T. Novak, “Heat pump market in Europe”, Apr. 2021, URL: <https://www.rehva.eu/rehva-journal/chapter/european-heat-pump-market>, [Accessed: 26-May-23].
- [7] EHPA, “Heat pump market data.” URL: <https://www.ehpa.org/market-data/#:-:text=2.18%20million%20heat%20pump%20units,of%20the%20heating%20market>, [Accessed: 17-July-23].
- [8] EHPA, “Heat pumps in figures: 2021 EU market and global outlook”, July 2022, URL: [https://www.ehpa.org/press\\_releases/record-growth-for-europes-heat-pump-market-in-2021/](https://www.ehpa.org/press_releases/record-growth-for-europes-heat-pump-market-in-2021/), [Accessed: 17-July-23].
- [9] P. M. Congedo, C. Baglivo, D. D’Agostino, and D. Mazzeo, “The impact of climate change on air source heat pumps,” *Energy Convers. Manag.*, vol. 276:116554, Jan. 2023, doi: 10.1016/j.enconman.2022.116554.
- [10] Z. Wehbi, R. Taher, J. Faraj, M. Ramadan, C. Castelain, and M. Khaled, “A short review of recent studies on wastewater heat recovery systems: Types and applications”, *Energy Rep.*, vol. 8, pp. 896-907, May 2022, doi: 10.1016/j.egy.2022.07.104.
- [11] P. J. Boait and R. Greenough, “Can fuel cell micro-CHP justify the hydrogen gas grid? Operating experience from a UK domestic retrofit”, *Energy and Buildings*, vol. 194, pp. 75-84, Jul. 2019, doi: 10.1016/j.enbuild.2019.04.021.
- [12] P. E. Dodds, I. Staffel, A. D. Hawkes, F. Li, P. Grünewald, W. McDowall, and P. Ekins, “Hydrogen and fuel cell technologies for heating: A review”, *International Journal of Hydrogen Energy*, vol. 5, pp. 2065-2083, Feb. 2015, doi: 10.1016/j.ijhydene.2014.11.059.
- [13] M. Sorace, M. Gandiglio and M. Santarelli, “Modeling and techno-economic analysis of the integration of a FC-based micro-CHP system for residential application with a heat pump”, *Energy*, vol. 120, pp. 262-275, Feb. 2017, doi: 10.1016/j.energy.2016.11.082.
- [14] IEA, “Heating”, Sept. 2022, URL: <https://www.iea.org/reports/heating>, [Accessed: 17-July-23].
- [15] M. Ristimäki, A. Säynäjoki, J. Heinonen, and S. Junnila, “Combining life cycle costing and life cycle assessment for an analysis of a new residential district energy system design”, *Energy*, vol. 63, pp. 168–179, Dec. 2013, doi: 10.1016/j.energy.2013.10.030.
- [16] M. K. Mattinen, A. Nissinen, S. Hyysalo, and J. K. Juntunen, “Energy Use and Greenhouse Gas Emissions of Air-Source Heat Pump and Innovative Ground-Source Air Heat Pump in a Cold Climate: Energy Use and Emissions of Heat Pumps”, *J. Ind. Ecol.*, vol. 19, no. 1, pp. 61–70, Feb. 2015, doi: 10.1111/jiec.12166.
- [17] ISO 14040:2006 (E), “Environmental management - life cycle assessment - principles and framework”.
- [18] ISO 14044:2006 (E), “Environmental management - life cycle assessment - requirements and guidelines”.
- [19] B. Greening and A. Azapagic, “Domestic heat pumps: Life cycle environmental impacts and potential implications for the UK”, *Energy*, vol. 39, no. 1, pp. 205–217, Mar. 2012, doi: 10.1016/j.energy.2012.01.028.
- [20] H. Lin, J. Clavreul, C. Jeandaux, J. Crawley, and I. Butnar, “Environmental life cycle assessment of heating systems in the UK: Comparative assessment of hybrid heat pumps vs. condensing gas boilers”, *Energy Build.*, vol. 240: 110865, Jun. 2021, doi: 10.1016/j.enbuild.2021.110865.
- [21] N. Shibata, F. Sierra and A. Hagrais, “Integration of LCA and LCCA through BIM for optimized decision-making when switching from gas to electricity services in dwellings”, *Energy and Buildings*, vol. 288: 113000, June 2023, doi: 10.1016/j.enbuild.2023.113000.
- [22] S. Sevindik, C. Spataru, T. Domenech Aparisi, and R. Bleischwitz, “A Comparative Environmental Assessment of Heat Pumps and Gas Boilers towards a Circular Economy in the UK”, *Energies*, vol. 14, no. 11, p. 3027, May 2021, doi: 10.3390/en14113027.
- [23] J.-I. Latorre-Biel, E. Jiménez, J. L. García, E. Martínez, E. Jiménez, and J. Blanco, “Replacement of electric resistive space heating by an air-source heat pump in a residential application. Environmental amortization,” *Build. Environ.*, vol. 141, pp. 193–205, Aug. 2018, doi: 10.1016/j.buildenv.2018.05.060.
- [24] A. C. Violante, F. Donato, G. Guidi, and M. Proposito, “Comparative life cycle assessment of the ground source heat pump vs air source heat pump,” *Renew. Energy*, vol. 188, pp. 1029–1037, Apr. 2022, doi: 10.1016/j.renene.2022.02.075.

- [25] C. Riva, T. C. Roumpedakis, G. Kallis, M. V. Rocco, and S. Karellas, “Life cycle analysis of a photovoltaic driven reversible heat pump”, *Energy Build.*, vol. 240, p. 110894, Jun. 2021, doi: 10.1016/j.enbuild.2021.110894.
- [26] A. Saoud, H. Harajli, and R. Manneh, “Cradle-to-grave life cycle assessment of an air to water heat pump: Case study for the Lebanese context and comparison with solar and conventional electric water heaters for residential application”, *J. Build. Eng.*, vol. 44: 103253, Dec. 2021, doi: 10.1016/j.jobte.2021.103253.
- [27] E. P. Johnson, “Air-source heat pump carbon footprints: HFC impacts and comparison to other heat sources”, *Energy Policy*, vol. 39, no. 3, pp. 1369–1381, Mar. 2011, doi: 10.1016/j.enpol.2010.12.009.
- [28] D. Saner, R. Juraske, M. Kübert, P. Blum, S. Hellweg, and P. Bayer, “Is it only CO<sub>2</sub> that matters? A life cycle perspective on shallow geothermal systems”, *Renew. Sustain. Energy Rev.*, vol. 14, no. 7, pp. 1798–1813, Sep. 2010, doi: 10.1016/j.rser.2010.04.002.
- [29] F. Knobloch, S. V. Hanssen, A. Lam, H. Pollitt, P. Salas, U. Chewpreecha, M. A. J. Huijbregts and J-F. Mercure, “Net emission reductions from electric cars and heat pumps in 59 world regions over time”, *Nat. Sustain.*, vol. 3, no. 6, pp. 437–447, Jun. 2020, doi: 10.1038/s41893-020-0488-7.
- [30] BSRIA, “BSRIA’s view on refrigerant trends in AC and Heat Pump segments”, Jan. 2020, URL: <https://www.bsria.com/us/news/article/bsrias-view-on-refrigerant-trends-in-ac-and-heat-pump-segments/>, [Accessed: 17-July-23].
- [31] European Commission, “EU legislation to control F-gases”, URL: [https://climate.ec.europa.eu/eu-action/fluorinated-greenhouse-gases/eu-legislation-control-f-gases\\_en](https://climate.ec.europa.eu/eu-action/fluorinated-greenhouse-gases/eu-legislation-control-f-gases_en), [Accessed: 17-July-23].
- [32] H. Maeng, J. Kim, S. Kwon, and Y. Kim, “Energy and environmental performance of vapor injection heat pumps using R134a, R152a, and R1234yf under various injection conditions”, *Energy*, vol. 280, p. 128265, Oct. 2023, doi: 10.1016/j.energy.2023.128265.
- [33] M. Longhini, MSc Thesis, “New generation refrigerants for domestic heat pumps in Sweden”, Portugal, Istituo Superior Tecnico Lisbon, 2015.
- [34] S. Rajabi Hamedani, M. Villarini, V. Marcantonio, U. di Matteo, D. Monarca, and A. Colantoni, “Comparative energy and environmental analysis of different small-scale biomass-fueled CCHP systems”, *Energy*, vol. 263: 125846, Jan. 2023, doi: 10.1016/j.energy.2022.125846.
- [35] M. Caduff, M. A. J. Huijbregts, A. Koehler, H.-J. Althaus, and S. Hellweg, “Scaling Relationships in Life Cycle Assessment: The Case of Heat Production from Biomass and Heat Pumps”, *J. Ind. Ecol.*, vol. 18, no. 3, pp. 393–406, May 2014, doi: 10.1111/jiec.12122.
- [36] W. Cyx, N. Renders, V. H. M., and S. Verbeke, “IEE TABULA - Typology Approach for Building Stock Energy Assessment”, Tech. Rep. August, 2011.
- [37] T. Fleiter, R. Elsland, M. Rehfeldt, and J. Steinbach, “Heat Roadmap Europe - Deliverable 3.1: Profile of heating and cooling demand in 2015 Data Annex.”, URL: [https://view.officeapps.live.com/op/view.aspx?src=https%3A%2F%2Fheatroadmap.eu%2Fwp-content%2Fuploads%2F2018%2F09%2FHRE4-Exchange-Template-WP3\\_v22b\\_website.xlsx&wdOrigin=BROWSELINK](https://view.officeapps.live.com/op/view.aspx?src=https%3A%2F%2Fheatroadmap.eu%2Fwp-content%2Fuploads%2F2018%2F09%2FHRE4-Exchange-Template-WP3_v22b_website.xlsx&wdOrigin=BROWSELINK), [Accessed: 10-June-23].
- [38] G. Wernet, C. Bauer, B. Steubing, J. Reinhard, E. Moreno-Ruiz, and B. Weidema, “The ecoinvent database version 3 (part I): overview and methodology”, *Int. J. Life Cycle Assess.*, vol. 21, no. 9, pp. 1218–1230, Sep. 2016, doi: 10.1007/s11367-016-1087-8.
- [39] M. Goedkoop, R. Heijungs, and M. Huijbregts, “ReCiPe 2008: a life cycle impact assessment method which comprises harmonized category indicators at the midpoint and the endpoint level, Report I: Characterisation”, 2008.
- [40] M. A. J. Huijbregts et al., “ReCiPe2016: a harmonised life cycle impact assessment method at midpoint and endpoint level”, *Int. J. Life Cycle Assess.*, vol. 22, no. 2, pp. 138–147, Feb. 2017, doi: 10.1007/s11367-016-1246-y.
- [41] J. Famiglietti, T. Toppi, L. Pistocchini, R. Scoccia, and M. Motta, “A comparative environmental life cycle assessment between a condensing boiler and a gas driven absorption heat pump”, *Sci. Total Environ.*, vol. 762, p. 144392, Mar. 2021, doi: 10.1016/j.scitotenv.2020.144392.
- [42] United Nations Environment Programme, “2010 report of the Refrigeration, Air Conditioning, and Heat Pumps Technical Options Committee”, Feb. 2011.
- [43] DAIKIN, “R-32: the most balanced refrigerant for stationary air-conditioners and heat pumps”, URL: <https://www.daikin.com/csr/information/influence/hfc32>, [Accessed: 17-July-23].
- [44] O. Mayorga Pérez and N. Yalavarthy, “Sustainability Review of the mobile cooling and climate control industry,” MSc Thesis, Sweden: KTH Royal Institute of Technology, 2020.
- [45] M. Weckert, “Comparative life cycle assessment of CFC-replacement compounds in different technical applications”, PhD Thesis, Germany: University of Bayreuth, 2008
- [46] EUNOMIA, “Impacts of leakage from refrigerants in heat pumps,” Mar. 2014.

- [47] A. D. Moore, T. Urmee, M. Anda, and E. Walker, "Life cycle assessment of domestic heat pump hot water systems in Australia", *Renew. Energy Environ. Sustain.*, vol. 2, p. 38, 2017, doi: 10.1051/rees/2017043.
- [48] K. N. Shah, N. S. Varandani, and M. Panchani, "Life Cycle Assessment of Household Water Tanks—A Study of LLDPE, Mild Steel and RCC Tanks", *J. Environ. Prot.*, vol. 07, no. 05, pp. 760–769, 2016, doi: 10.4236/jep.2016.75068.
- [49] "Rockwool - recycling rate", URL: <https://www.grodan.com/about/recycling-solutions/>, [Accessed: 17-July-23].
- [50] "Chemical recycling of polyurethane waste." URL: <https://www.recycling-magazine.com/2020/07/31/chemical-recycling-of-polyurethane-waste/>, [Accessed: 10-June-23].
- [51] C. Protopapadaki, "A probabilistic framework towards metamodeling the impact of residential heat pumps and PV on low-voltage grids", PhD Thesis, Belgium: KU Leuven, Dec. 2018.
- [52] C. Verhelst, F. Logist, J. Van Impe, and L. Helsen, "Study of the optimal control problem formulation for modulating air-to-water heat pumps connected to a residential floor heating system", *Energy Build.*, vol. 45, pp. 43–53, Feb. 2012, doi: 10.1016/j.enbuild.2011.10.015.
- [53] Daikin Altherma, URL: [https://www.daikin.es/en\\_us/for-your-home/heating-daikin-altherma.html](https://www.daikin.es/en_us/for-your-home/heating-daikin-altherma.html), [Accessed: 17-July-23].
- [54] D. Saelens and C. Protopapadaki, "Heat pump and PV impact on residential low-voltage distribution grids as a function of building and district properties", *Appl. Energy*, vol. 192:268–81, Apr. 2017, doi: 10.1016/j.apenergy.2016.11.103.
- [55] Toleikyte, A., Roca Reina, J.C., Volt, J., Carlsson, J., Lyons, L., Gasparella, A., Koolen, D., De Felice, M., Tarvydas, D., Czako, V., Koukoufikis, G., Kuokkanen, A. and Letout, S., "The Heat Pump Wave: Opportunities and Challenges", Publications Office of the European Union, Luxembourg, *JRC134045*, June 2023, doi:10.2760/27877.
- [56] R. Renaldi, A. Kiprakis, and D. Friedrich, "An optimisation framework for thermal energy storage integration in a residential heat pump heating system," *Appl. Energy*, vol. 186, pp. 520–529, Jan. 2017, doi: 10.1016/j.apenergy.2016.02.067.
- [57] Emergen Research, "Underfloor Heating Market, By Product (Hydronic and Electric), By Installation (New Installation and Retrofit Installation) By Application (Residential, Commercial and Others) and By Region Forecast to 2030", Jun. 2022, URL: <https://www.emergenresearch.com/industry-report/underfloor-heating-market>, [Accessed: 17-July-23].
- [58] R. M. Lazzarin, "Condensing boilers in buildings and plants refurbishment", *Energy Build.*, vol. 47, pp. 61–67, Apr. 2012, doi: 10.1016/j.enbuild.2011.11.029.
- [59] T. Loga, "TABULA Calculation Method – Energy Use for Heating and Domestic Hot Water," URL: [https://episcopo.eu/fileadmin/tabula/public/docs/report/TABULA\\_CommonCalculationMethod.pdf](https://episcopo.eu/fileadmin/tabula/public/docs/report/TABULA_CommonCalculationMethod.pdf) [Accessed: 16-Dec-2023]
- [60] ASHRAE, "Winter design temperatures," 2009.
- [61] Daikin Condensing gas boiler, URL: [https://www.daikin.eu/en\\_us/product-group/gas-condensing-boilers.html](https://www.daikin.eu/en_us/product-group/gas-condensing-boilers.html), [Accessed: 17-July-23].
- [62] R. Frischknecht, N. Jungbluth, H-J. Althaus, G. Doka, R. Dones, T. Heck, S. Hellweg, R. Hischier, T. Nemecek, G. Rebitzer and M. Spielmann "The ecoinvent Database: Overview and Methodological Framework", *Int. J. Life Cycle Assess.*, vol.10, pp. 3-9, Jan. 2005, doi: 10.1065/lca2004.10.181.1.
- [63] C. Chengmin, Z. Yufeng and M. Lijun, "Assessment for central heating systems with different heat sources: a case study", *Energy Build.*, vol. 48, pp. 168-174, May 2012, doi: 10.1016/j.enbuild.2012.01.025
- [64] C. Yang, S. Seo, N. Takata, K. Thu, and T. Miyazaki, "The life cycle climate performance evaluation of low-GWP refrigerants for domestic heat pumps," *Int. J. Refrig.*, vol. 121, pp. 33–42, Jan. 2021, doi: 10.1016/j.ijrefrig.2020.09.020
- [65] D. Burchart-Korol, P. Pustejovska, A. Blaut, S. Jursova, and J. Korol, "Comparative life cycle assessment of current and future electricity generation systems in the Czech Republic and Poland", *Int. J. Life Cycle Assess.*, vol. 23, no. 11, pp. 2165–2177, Nov. 2018, doi: 10.1007/s11367-018-1450-z.
- [66] M. A. J. Huijbregts, Z. J. N. Steinmann, P. M. F. Elshout, G. Stam, F. Verones, M. Vieira, M. Zijp, A. Hollander and R. Van Zelm, "ReCiPe 2016: a life cycle impact assessment method which comprises harmonized category indicators at the midpoint and the endpoint level", *Int. J. Life Cycle Assess.*, vol. 22, pp. 138-147, Nov. 2016, doi: 10.1007/s11367-016-1246-y.
- [67] IEA, "The Future of Heat Pumps", URL: <https://www.iea.org/reports/the-future-of-heat-pumps/executive-summary> [Accessed: 11-Dec-2023]
- [68] A. Acero, C. Rodriguez, and A. Ciroth, "Impact assessment methods in Life-cycle assessment and their impact categories," 2015, URL: <https://www.openlca.org/wp-content/uploads/2015/11/LCIA-METHODS-v.1.5.4.pdf> [Accessed: 11-Dec-2023]
- [69] B. O. Bolaji and Z. Huan, "Ozone depletion and global warming: Case for the use of natural refrigerant – a review," *Renew. Sustain. Energy Rev.*, vol. 18, pp. 49–54, Feb. 2013, doi: 10.1016/j.rser.2012.10.008.
- [70] S. Konghuayrob and K. Khositkullaporn, "Performance Comparison of R32, R410A and R290 Refrigerant in Inverter Heat Pumps Application", presented at the International Refrigeration and Air Conditioning Conference, 2016.

- [71] Å. L. Sørensen, H. T. Walnum, I. Sartori, and I. Andresen, “Energy flexibility potential of domestic hot water systems in apartment buildings”, *E3S Web Conf.*, vol. 246, p. 11005, 2021, doi: 10.1051/e3sconf/202124611005.
- [72] K. Treyer, C. Bauer, and A. Simons, “Human health impacts in the life cycle of future European electricity generation”, *Energy Policy*, vol. 74, pp. S31–S44, Dec. 2014, doi: 10.1016/j.enpol.2014.03.034.
- [73] E. K. Velten, N. Evans, D. Spasova, M. Duwe, R. De La Vega, L. Duin and H. Brannern, “Charting a path to net zero: An assessment of national long-term strategies in the EU”, Ecologic Institute, Berlin, 2022.