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Towards integral assessment of heat pumps and refrigerants using LCA: A case study for the German building stock

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Abstract

Heat pumps are the key technology to defossilize the heat supply of buildings, which for now is predominantly based on burning fossil fuels. In Germany, 19 Million residential buildings consume about 865 TWh of fossil fuels and emit about 120 Million tons of CO2 each year, mainly for heating purposes. Reducing GHG emissions is critical to achieving climate goals, and replacing combustion-based heating technologies is crucial to GHG mitigation. To recommend appropriate alternative technologies and accelerate the corresponding deployment, there are standardized indicators for heat pumps in each sustainability dimension: For instance, economic and environmental aspects can be represented by energy labels, while social aspects (e.g., acoustics) are currently not in focus. In particular, from an environmental point of view, the focus is on labeling emissions due to the refrigerants' Global Warming Potential (GWP) and operating-related emissions. However, the focus on GHG emissions bears the risk of unnoticed burden shifting to other environmental impacts, such as ecotoxicity or land use. To avoid burden shifting, a holistic assessment of heat pumps and refrigerants using life cycle assessment (LCA) is necessary.

This work investigates the environmental assessment metrics beyond climate change and applies them to heat pumps and refrigerants in existing buildings in Germany. To evaluate essential assessment metrics simultaneously, a fundamental data basis is prepared through an extensive literature and database review. While there is scientific consensus on the fundamental understanding of heat pumps and refrigerants, some assumptions still need to be made to obtain meaningful results. Therefore, a key finding of this work is that further research is mandatory. In addition, we identify the main contributors to improving the environmental impacts of heat pumps and refrigerants using LCA: For low GWP refrigerants in heat pumps, the refrigerant choice is less important in terms of environmental aspects, here resource availability (flour range) and proper handling (avoidance of leakage) are essential. Currently, emissions from electricity generation dominate the environmental impacts of heating with heat pumps. Using renewable electricity instead will lead to some burden shifting but reduce most environmental impacts so that the production of heat pumps and refrigerants gains importance for further impact reduction. For future research, consider potential improvements in the supply chains of materials and refrigerants using dynamic LCA.

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Keywords: Environmental impact, low-emission heating, burden-shifting

1. Introduction

To adjust to comfortable indoor conditions, heating and cooling are crucial in the building sector. Particularly during the heating season, the building sector throughout Europe requires enormous energy to meet its heating demands. Currently, most residential heating systems are based on conventional combustion

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technologies, which cause greenhouse gas (GHG) emissions during operation, mainly in the form of CO_2. However, GHG emissions must be drastically reduced by 2050 to achieve climate targets. In this context, the transition to low-carbon heating systems is taking place with increasing acceleration replacing conventional with heat pump-based systems. Heat pumps use refrigerants to upgrade environmental heat and provide suitable heat for buildings. The upgrading requires an additional energy supply to raise the temperature level of environmental heat. In building applications, the energy supply powers an electricity-driven compressor with refrigerant-dependent efficiency. Therefore, the overall heat pump performance and emission reduction potential depend mainly on the refrigerant and the refrigerant-dependent compressor efficiency. In the past, heat pumps used refrigerants (Hydrochlorofluorocarbons, HCFC) that were very efficient and simultaneously neither flammable nor toxic. These favorable properties were achieved using fluorine (F) and chlorine (C) atoms in the hydrocarbon chains of the refrigerant. However, in the event of a leak, chlorine was released into the atmosphere, contributing to ozone depletion. Therefore, refrigerants with ozone depletion potential (ODP) were largely banned. [1]

The ban has led to the developing of new refrigerants that are also efficient and safe but do not require a chlorine atom to make a stable molecule. This group of refrigerants is called hydrofluorocarbons (HFCs), which consist of hydrocarbons and fluorine. However, many HFCs have high global warming potential (GWP) due to the fluorine atoms. Therefore, in the event of leakage, HFCs would contribute to global warming and climate change. Therefore, HFCs should also be used less or even completely banned in heat pumps to comply with long-term climate targets to reduce this risk. According to current research, the most superior alternatives for the future are natural refrigerants such as hydrocarbons (HCs) or other organic refrigerants such as ammonia or CO_2 and hydrofluorolefines (HFOs). These refrigerant groups have no ODP and a low GWP (<150), thus potentially not compromising climate goals. However, future refrigerants must also be very efficient to achieve a high performance of heat pumps and, accordingly, low GHG emissions. [2]

To extend the environmental assessment of refrigerants to heat pumps, the (extended) Total Equivalent Warming Impact (eTEWI) [3], [4] or Lifecycle Climate Performance (LCCP) [5] evaluation methods are often used in the current literature. Both methods focus on evaluating the climate change impact of refrigerants and heat pumps' operation, i.e., the electricity consumption of the compressor. However, in the future, regenerative energy sources can reduce the climate impact of the operation, potentially shifting the impact to other life cycle stages, e.g., emissions from the production of heat pumps, or increase other environmental impacts, which is called burden shifting. To avoid burden shifting, more advanced environmental assessment methods must be applied, which consider further impact categories. For example, in addition to operation, the heat pump's production, disposal, and recycling will gain importance. However, the influence of these phases is insufficiently considered in current methods. Therefore, Life Cycle Assessment (LCA) [6] is needed to consider all phases and impacts adequately. Moreover, in the early design stages, LCA will already help identify potential environmentally friendly refrigerants that have less impact on the environment than conventional refrigerant groups.

Compared to conventional eTEWI and LCCP, this work investigates the environmental assessment metrics beyond climate change by using LCA and applies them consistently to heat pumps and refrigerants in existing buildings in Germany. An LCA model is formulated to evaluate essential assessment metrics simultaneously (Section 2), and an extensive literature and database review provide relevant information and assumptions. As a case study (Section 3), we use seven refrigerants in a simple heat pump cycle and assess 16 environmental impact categories. For discussion (Section 4), we apply different electricity mixes and compare our results to a conventional gas boiler system. Finally, we summarize our findings and give a perspective for future work (Section 5).

2. LCA Modelling

This section addresses the Goal and Scope definition (Section 2.1) of this study, the Life Cycle Inventory (LCI, Section 2.2), and the data sources (Section 2.3).

2.1. Goal and Scope Definition

The LCA serves for the environmental evaluation of heat pumps and refrigerants in residential buildings in Germany. The LCA aims to investigate the influence of the refrigerant on the GHG emissions caused within the life cycle of a heat pump. In addition, trade-offs with other environmental categories will be considered, and levers to reduce the overall environmental impact will be identified.

This work investigates the life cycle of a simple air-to-water heat pump according to Figure 1. While the production of refrigerants and heat pumps and the operation of the heat pumps are in the foreground of the investigations (red), additional aspects (black) must also be modeled to develop reasonable conclusions. The function of the air-to-water heat pump is to provide space heating over an observation period of 20 years, matching the heat pump's lifetime [7]. This paper does not consider other parts of the building energy system, such as the distribution system, the buffer tanks, or the building envelope, as this work is intended to provide a basis. However, these other parts of the building energy system should be integrated into future work. The functional unit in the LCA is the provision of space heating for a German residential building over the heat pump's life cycle (20 years). The system boundaries include the production of refrigerant and heat pump, the operation of the heat pump, any leakage of refrigerant, and upstream processes, e.g., materials and energy. In contrast to the LCCP method, the recycling of heat pump and refrigerant is not included in the system boundaries, as there are no sufficient data sets for the environmental impacts of the recycling processes.

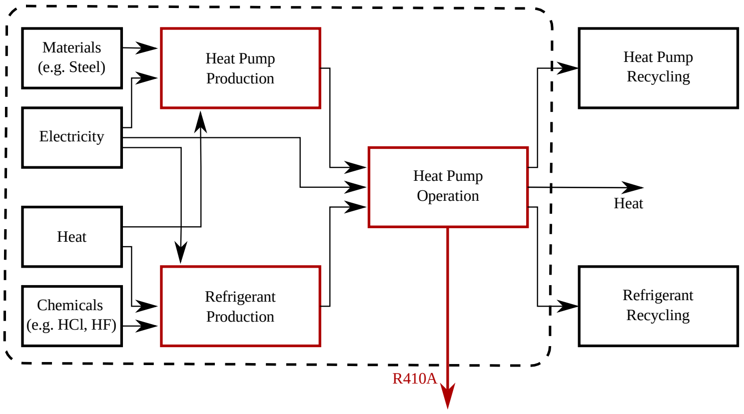

Figure 1: Life cycle of an air-water heat pump and assumed system boundaries.

This study follows the ILCD (International Life Cycle Data system) recommendations to characterize elementary flows to environmental impacts, comprising 16 environmental impact categories, e.g., climate change, acidification, and ozone depletion [8], [9]. All 16 categories are assessed, while the focus lies on climate change.

2.2. Life Cycle Inventory

To conduct the LCA, we need a sound basis comprising the assumptions within the calculation procedure. Table 1 sums up all assumptions depending on the refrigerant. To exchange the conventional refrigerant R410A, we investigate six potential refrigerants with lower GWP than 1000 and no ODP from four substance groups: R1234yf (HFO), R32 (HFC), R290, R1270, and R600a (HC), and R717 (Anorganic). Except for R717 (safety class B), all refrigerants are assigned to safety class A. However, all potential refrigerants are at least low flammable (2L and higher). Thus, if one of these six refrigerants prevails in the long term, increased safety requirements will be imposed on heat pumps. To assess the environmental impacts concerning the entire life cycle, we need additional information about the production (refrigerant and heat pump), the heat pump operation, and refrigerant leakage during the heat pump operation and end-of-life (EOL).

Table 1: Main assumptions to model the life cycle of an air-water-heat pump. Most of the assumptions are independent of the refrigerant choice, while some are influenced by the refrigerant.

Refrigerant	R410A	R32	R1234yf	R290	R1270	R600a	R717
Group	HFC	HFC	HFO	HC	HC	HC	Anorganic
Safety Class	A1	A2L	A2L	A3	A3	A3	B2L
GWP_{100}	2,256	771	4	3	1.8	4	0
Heat pump operation							
SCOP / -	3.71	3.99	3.82	4.20	4.19	3.81	4.27

Annual Heat Demand	20,400 kWh	20,400 kWh	20,400 kWh	20,400 kWh	20,400 kWh	20,400 kWh	20,400 kWh
Maximum Heat Demand	7.5 kW	7.5 kW	7.5 kW	7.5 kW	7.5 kW	7.5 kW	7.5 kW
Refrigerant	R410A	R32	R1234yf	R290	R1270	R600a	R717
Heat pump production							
Specific HP size	18 kg/kW	18 kg/kW	18 kg/kW	18 kg/kW	18 kg/kW	18 kg/kW	18 kg/kW
Mass Composition HP	Heck et al.	Heck et al.	Heck et al.	Heck et al.	Heck et al.	Heck et al.	Heck et al. w/o Copper
Refrigerant production							
Specific Refrigerant charge	0.3 kg/kW	0.25 kg/kW	0.35 kg/kW	0.15 kg/kW	0.15 kg/kW	0.15 kg/kW	0.1 kg/kW
Production Impacts	Frischknecht	Frischknecht	Baral et al.	ecoinvent	ecoinvent	ecoinvent	ecoinvent
Leakage rate / production	1% total	1% total	1% total	-	-	-	-
Refrigerant Leakage							
Leakage rate / operation	5 %/a	5 %/a	5 %/a	5 %/a	5 %/a	5 %/a	5 %/a
Leakage rate / EOL	30 %	30 %	30 %	30 %	30 %	30 %	30 %

2.2.1. Refrigerant Production

While potential environmental impacts are known and available in ecoinvent [10] for producing natural refrigerants R290, R1270, R600a, and R717, few primary sources exist for the refrigerants R410A, R32, and R1234yf, which generally consider only GHG emissions. Therefore, for R410A and R32 production, data sets from Frischknecht et al. are used [11], [12]. Frischknecht models the production of refrigerants using chemical reaction equations with additional assumptions about the energy required, recovery, chemical leakage, and the production route. Data sets from Baral et al. are used for R1234yf production [13]. Baral et al. study the GHG emissions from the production of R1234yf using the CHEMCAD simulation tool. The reported production process starts with the reactants chlorotrifluoroethylene and chloromethane. Moreover, leakages of chemicals, reactants, or intermediates can occur during refrigerant production. In particular, the leaking of substances with high GWP or ODP can account for a large portion of the total environmental impact of production and thus have to be modeled for a holistic assessment. As a first estimate, an emission rate of one mass percent is assumed, made up of the reactants and intermediates.

The required charge in the heat pump depends on the refrigerant considered and determines the amount of refrigerant that needs to be produced. Commercial heat pumps for residential buildings exist for the three refrigerants R410A, R32, and R290 so that data sheets can be accessed. The data sheets approximate the specific charge for R410A, R32, and R290. The specific charge of the remaining refrigerants is estimated using the UNEP report published in 2014 [14]. In addition to the amount of refrigerant required for operation, we consider the heat pump production and refrigerant leakage that may occur during operation. The leakage reduces the heat pump's charge, so refilling the system becomes necessary to ensure its efficiency.

2.2.2. Heat Pump Production

The mass composition of the heat pump under study is based on a 10 kW brine-to-water heat pump from Hoval, operated with R134a. In Heck et al. [15], the masses and compositions of the individual components are reported. The mass composition of a heat pump will vary depending on the production company and the choice of components used. Since no known mass compositions of heat pumps operating with the refrigerants studied, the mass composition is used for all refrigerants studied except R717 (Figure 2).

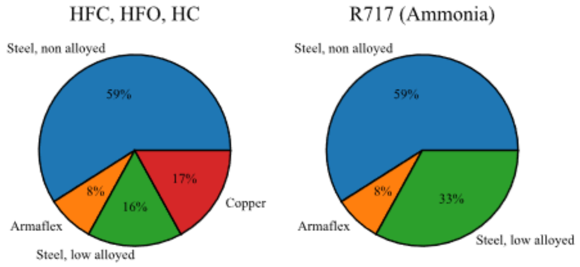

Figure 2: Mass composition of the studied air-water heat pumps.

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

The specific gravity of the heat pump depends on the design of the heat pump and the refrigerant used. The volumetric heating capacity (VHC) influences the required installation space as well as the size of the heat pump. In addition, the required wall thicknesses of the tubes depend on the maximum operating pressures of the heat pumps, which are determined by the refrigerant used. Examining data sheets of commercial heat pumps results in a specific weight of 15 kg/kW for heat pumps operating with R32 and R410A and a specific weight of 20 kg/kW for heat pumps operating with R290. Differences could not be attributed to the refrigerant and thus might result from design choices by the manufacturers. To the author's knowledge, no publication exists that examines the refrigerant's influence on the heat pump's weight in isolation from other influencing factors. Therefore, the same specific weight of 18 kg/kW is assumed for all refrigerants, as it is the average of the reported specific weight based on manufacturer data. In addition to the environmental impacts from material production, we consider the heat pump's assembly and the subcomponents' manufacture using the generic ecoinvent data set for metalworking.

2.2.3. Refrigerant Leakage

Leakage to the atmosphere results in different environmental effects depending on the refrigerant. As described in Section 1, the use of CFCs was regulated by the Montreal Protocol in 1989 because leakage of CFCs depletes the ozone layer. While the refrigerants studied in this work do not have ODP as a measured characteristic, i.e., do not cause ozone layer depletion when released, refrigerant leakage may contribute to the heat pump's total impact in other environmental categories. This work assumes a leakage rate L_{Use} of 5% per year in operation and a leakage rate L_{EOL} of 30 % at the end of life (EOL) [16], [17]. Although leakage of refrigerants has no direct impact on ozone layer depletion, during the production of some of the refrigerants, leakage of intermediates (see 2.2.1.) can cause ozone layer depletion, which we attribute to refrigerant manufacturing.

2.2.4. Heat Pump Operation

Since a large share of the emissions is related to indirect emissions from electricity consumption, it is critical to consistently model the energy demand of the buildings and the corresponding heat pump operation. The heat pump operation is driven by the building's heat demand, which is determined via TEASER [18]. TEASER is a framework for data enrichment of building performance simulation models to simplify simulating the heat demand of buildings, neighborhoods, and city districts. Based on the location, building type, building area, year of construction, and modernization standard, TEASER approximates the building's envelope area and insulation standard. In this paper, a two-story single-family house in Aachen is considered. The building has a living area of 150 m^2 and an insulation standard according to the 2nd Thermal Insulation Ordinance of 1984.

As the building model's boundary condition serves a weather data set (Test Reference Year (TRY), 2015) representing an hourly resolved annual temperature profile. The TRY data set used represents Aachen to match the building location and was published by the German Weather Service. In general, TRY data sets exist for each square kilometer in Germany. Thus, spatially-resolved temperature profiles can be used in further studies to exploit the change of environmental impacts depending on the location.

TEASER enriches a parameterized building performance simulation model with data sets and a weather data set to create a simulation model. Then, the energetic performance is calculated based on the heat demand, which is required to balance heat losses to the environment while maintaining an indoor air set temperature, which is 21 °C in our case study (cf. Figure 3). In total, the annual heat demand of the considered building is about 20,400 kWh with a maximum heat load $\dot{Q}_{\mathrm{max}}$ of 7.5 kW.

To meet the building's heating demand based on the outdoor air temperature, a heating system is required. We use an air-to-water heat pump model to provide heat that meets the hourly resolved demand. Outdoor air temperature and heating demand serve as the boundary condition for the calculation procedure. The nominal flow temperature is calculated using a conventional heating curve. The heat pump model includes a fluid dependency and calculates the fluid behavior in a basic refrigeration cycle, according to Figure 4. The model is used from Hoeges et al. and covers fluid dependence with a validated loss-based compressor model.

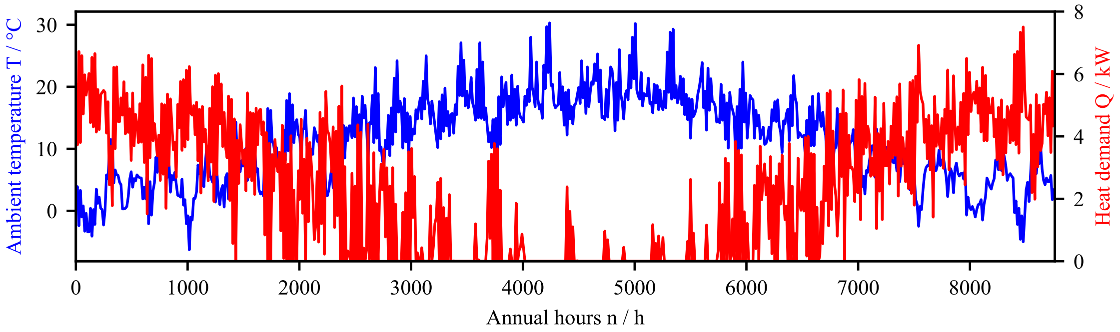

Figure 3: Hourly resolved temperature profile and corresponding heating demand of the investigated building.

Based on the boundary conditions, the heat pump model optimizes the pressure levels in the evaporator and the condenser. In addition, the degree of subcooling at the condenser outlet and the degree of superheating at the compressor inlet is maximized for each operating point subject to maximum Coefficient of Performance (COP). For more details on the heat pump model we refer to Hoeges et al. [2]. Using the heat pump model, the heat demand profile, and the outdoor air temperature profile, the required electrical power for space heating is determined for each refrigerant.

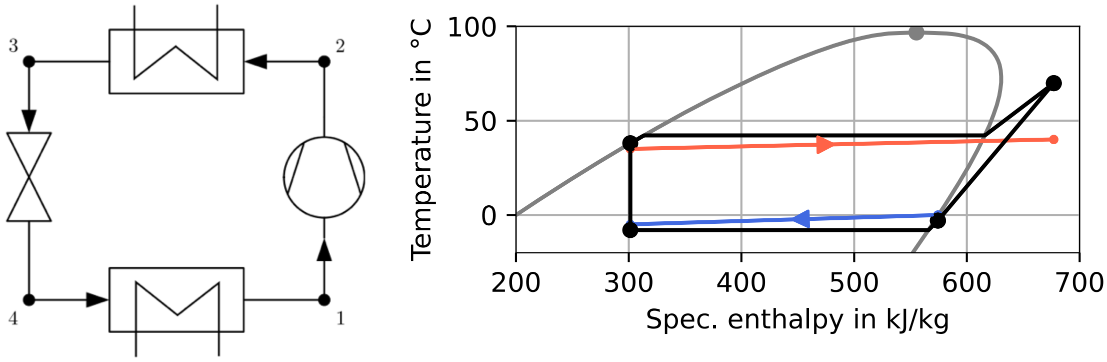

Figure 4: Process scheme (left) and exemplary T-h diagram (right) of a simple heat pump circuit.

2.3. Data Sources and Calculation of Environmental Impacts

This work uses the LCA database ecoinvent [10] to obtain the environmental impacts of material and energy used for the production of refrigerants, the construction and operation of heat pumps. (cf. Table 1).
The ecoinvent datasets already contain the characterization models and, thus, the environmental impacts of each material or energy flow needed in this study. When using the ecoinvent datasets, the environmental impacts must be scaled by the amount of material or energy flow necessary to supply the functional unit. The characterization factors for elementary flows representing refrigerants are used to estimate the impact of refrigerant leakage. The characterization factors indicate the extent to which the refrigerant leakage contributes to an impact category.

3. Life Cycle Impact Assessment

In this section, we provide the general Life Cycle Impact Assessment and conduct a sensitivity study with respect to the grid mix.

3.1. General Assessment

The electricity demand from heat pump operation accounts for the largest share of the total environmental impacts in most categories (orange, Figure 5). The only exception is ozone depletion of fluorine-containing refrigerants due to leakage of intermediates during the refrigerant production. In all other categories, refrigerant production is negligible, and heat pump production is the second largest contributor to environmental impacts. In particular, heat pump production results in significant environmental impacts in ecotoxicity, human toxicity, and resource consumption for all refrigerants except the R717 due to not involving copper (see Section 2.2.2).

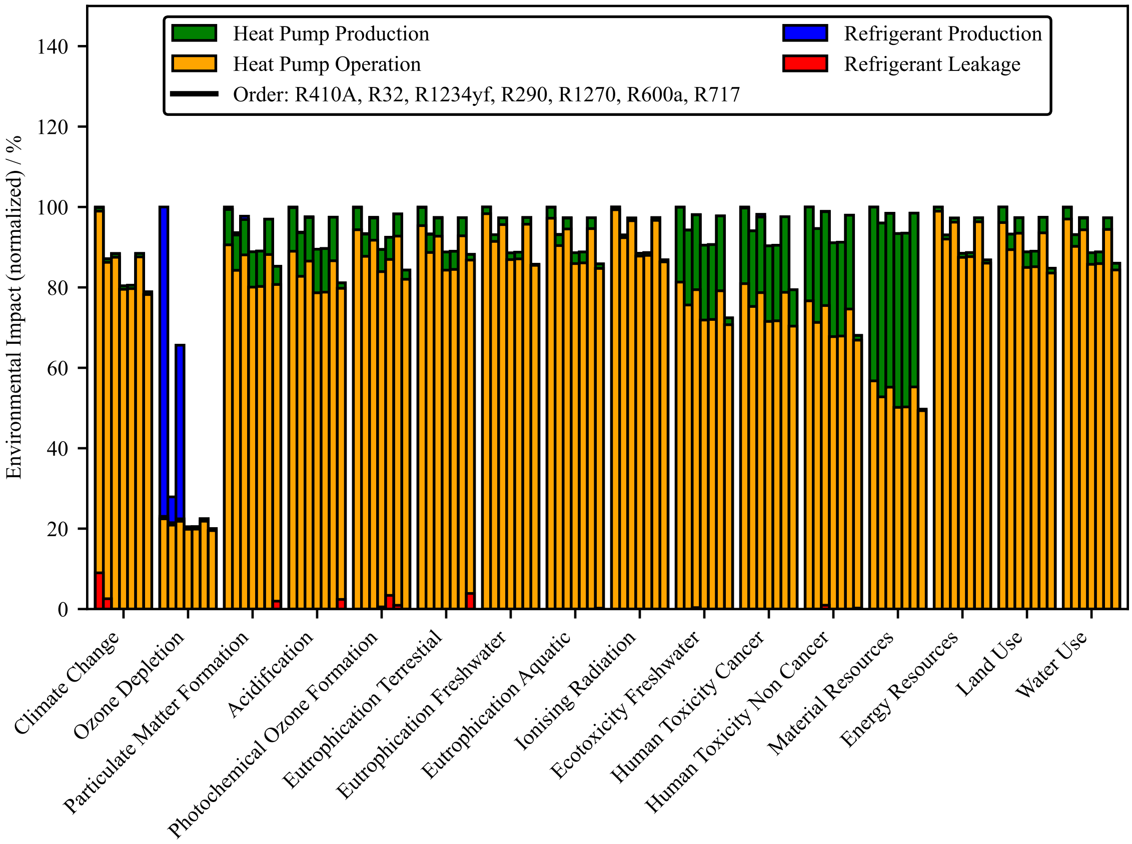

Figure 5: Environmental impacts of a heat pump for each environmental category and each refrigerant (normalized to R410A). Considered is heat supply over 20 years using the German electricity mix (2018) (521 gCO_2/kWh). The shares of the individual phases are color-coded.

Refrigerant leakage during the operation (red) is the smallest contributor and depends on the refrigerant and the environmental category: The high-GWP refrigerants R410A and R32 lead to an increase in GHG emissions and leakage of the toxic refrigerant R717 leads to minor environmental impacts, in particulate matter formation, acidification, and terrestrial eutrophication.

Across all refrigerants, R717 causes the lowest environmental impacts in all categories due to the high efficiencies. Due to the high SCOP that can be achieved with R717, the electricity required to operate the heat pump is lower, resulting in lower environmental impacts. In addition, the production of the R717 heat pump causes lower environmental impacts. Since the environmental impacts are lowest for a heat pump with R717, the refrigerant R717 is recommended in the context of a purely environmental evaluation. After R717, the environmental impacts are lowest for the hydrocarbons R290 and R1270. The use of R290 and R1270 allows high efficiencies and thus lower environmental impacts due to electricity demand than the HFOs and R600a. The next efficient refrigerant is R32. A disadvantage is the high GWP, so the leakage of R32 significantly increases GHG emissions. Using R600a and R1234yf causes high environmental impacts due to the lower efficiencies. The highest environmental impacts in all environmental categories are caused by using R410A with the lowest efficiency. Moreover, R410A leakage significantly increases GHG emissions. The production of R410A also causes the highest environmental impacts in the ozone depletion category. Since the electricity demand and the grid mix have the highest influence on all environmental impacts, we analyze its sensitivity.

3.2. Influence of Grid Mix

The environmental impacts of the heat pump (Figure 5) were calculated assuming the German electricity mix from 2018 (GE) for the heat pump's entire lifetime. However, the share of renewable energies in electricity production is forecast to increase while the share of fossil fuels is forecast to decrease. Thus, in the following, we assume a dynamic electricity mix (GE-to-SDS) that changes over the heat pump's lifetime to account for the influence of possible decarbonization. We assume a linear progression between the German electricity mix from 2018 and the European electricity mix from the Sustainable Development Scenario (SDS) of the International Energy Agency (IEA) for 2040 [19]. The Sustainable Development Scenario models the measures needed to achieve the goals of the Paris Climate Agreement. The resulting environmental impacts of the heat pump considering the GE-to-SDS electricity mix (Figure 6).

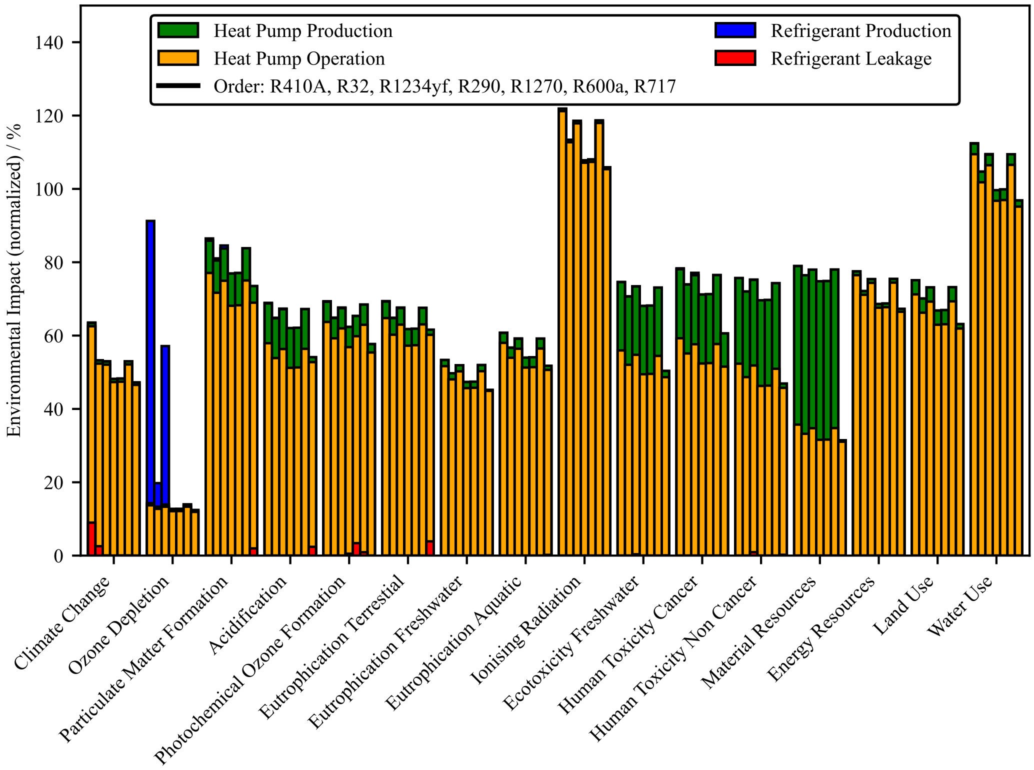

Figure 6: Sensitivity analysis of electricity mix (normalized to refrigerant R410A with German electricity mix). Instead of the static, German electricity mix, a more and more sustainable electricity mix is assumed (GE-to-SDS), where specific CO_2 emissions decrease linearly over the lifetime of the heatpump, from 521 gCO_2/kWh (GE) to 114 gCO_2/kWh (SDS). The environmental impacts of the heat pump are normalized to the refrigerant R410A with the static German electricity mix from 2018.

The environmental impacts of the heat pump decrease in most environmental categories due to a higher share of renewable energy sources and nuclear energy compared to the German electricity mix. Only ionizing radiation and water demand increase due to the higher proportion of nuclear and hydro energy in the SDS electricity mix. Not only do the environmental impacts in most environmental categories decrease due to the change in the electricity mix, but the ranking of refrigerants is also affected. For example, for the static German electricity mix, the R32 heat pump produces lower GHG emissions than the heat pumps of the low-GWP refrigerants R1234yf and R600a due to good efficiency despite leakage (see Figure 6). For the GE-to-SDS electricity mix, this statement is no longer valid, as GHG emissions are higher for the use of R32.

Furthermore, changing the electricity mix does not affect the environmental impacts from production of heat pump and refrigerant, even though these phases require electricity. This is because the production is based on aggregated datasets from ecoinvent, which does not directly allow to exchange the electricity mix, e.g., for the upstream copper production. The refrigerant leakage is also unaffected since no electricity is involved.

4. Discussion

To evaluate whether changing from a gas condensing heating system to an air-to-water heat pump increases or decreases the enviromental impact we show a list of all impact categories and different grid mixes in Table 2. A heat pump with R410A refrigerant is used for the comparison to conservatively assess potential GHG mitigation. For this comparison, the SCOP of the heat pump is based on measured values of air-to-water heat pumps in the field. The SCOP of 3.1 used comes from the research project WPsmart in the inventory of Fraunhofer ISE. The gas condensing heating system is modeled using an ecoinvent dataset. Table 2 shows that the heat pump’s potential to reduce environmental impacts depends on the electricity mix and the impact category. If the heat pump would use the current German electricity mix (GE) throughout its entire life cycle, GHG emissions decrease by 30% compared to the gas condensing system.

Further reductions are expected in ozone depletion, photochemical ozone formation and energy resources. All other environmental categories increase significantly. The GE-to-SDS electricity mix approximates the electricity mix of a heat pump installed in 2020 that has a 20-year lifetime. In the GE-to-SDS electricity mix, the environmental categories increase or decrease in the same environmental categories. In the climate change categories, the changing electricity mix achieves a higher reduction in GHG emissions (-54%). Further significant savings are also possible in the ozone depletion, and energy resources. In the remaining environmental categories, except for ionizing radiation and water consumption, the environmental impacts increase less for the GE-to-SDS electricity mix than for the GE electricity mix.

While the environmental impacts of switching to a heat pump with the GE-to-SDS electricity mix can only be reduced in 4 out of 16 environmental categories, the number increases to 9 out of 16 for the static SDS electricity mix. Using the SDS electricity mix, a heat pump reduces GHG emissions by 79% down to one-fifth of the GHG emissions that would be caused by providing space heating through gas heating.

By switching to the SDS electricity mix, the environmental impacts of a heat pump can be significantly reduced compared to the GE electricity mix in all environmental categories except ionizing radiation and water consumption. Furthermore, the less environmental impact caused by the generation of the purchased electricity, the better the air-to-water heat pump performs in an environmental comparison with a gas condensing boiler. In addition to the three electricity mixes, the comparison between gas heating and heat pumps is listed for electricity supply by wind power and photovoltaic (PV) technologies. The data sets for both technologies come from ecoinvent [10]. The use of wind power can reduce GHG emissions by 89%, and environmental impacts are reduced in 11 of 16 environmental categories. With the use of PV, a reduction of 81% is possible, or in 8 of 16 environmental categories.

To summarize, in the categories of climate change, ozone depletion, photochemical ozone formation, and energy resource consumption, environmental impacts can be reduced for all five electricity mixes. However, in the categories of eutrophication, freshwater, and human toxicity, the environmental impacts of carcinogenic, resource consumption, and water consumption increase when switching to a heat pump for all five electricity mixes. The environmental impacts cannot be reduced in all environmental categories, even if renewable energy sources, wind power, and photovoltaics provide electricity.

When switching from a gas condensing heating system to a heat pump, burden-shifting always occurs. Burden shifting describes the increase of environmental impacts in one or more impact categories when reducing environmental impacts in another category. For example, when switching from a gas condensing heating system to an air-to-water heat pump, GHG emissions can be saved, while environmental impacts increase in other environmental categories.

The extent to which burden-shifting is acceptable depends on the environmental categories affected. Reducing GHG emissions is currently a high priority, so burden-shifting could be acceptable. The Planetary Boundary framework provides an initial guide for assessing whether burden-shifting compromises the overall sustainability. Planetary Boundaries are boundaries in nine categories, the crossing of which threatens the stability of the Earth's ecosystem. Climate change is one of the nine categories. Other categories address the biogeochemical cycles of nitrogen and phosphorus, freshwater use, and land use. However, an exact mapping between the EF environmental categories used in this study and the Planetary Boundaries is only partially possible. Five of the nine boundaries have already been transgressed so that burden-shifting to these categories should be avoided. These categories among others include climate change, land-system change (similar to land use), and the biogeochemical cycles of nitrogen and phosphorus (similar to eutrophication), which are also addressed in the EF environmental categories.

Table 2: Changes of the environmental impact when switching from a gas condensing heating system to an air-to-water heat pump depending on the electricity mix. The gas heating system is used as a reference. (R410A, n = 20 a, SCOP = 3.1)

	GE (521 gCO_2/kWh)	GE-to-SDS (317 gCO_2/kWh)	SDS (114 gCO_2/kWh)	Wind Energy (32 gCO_2/kWh)	Photovoltaic (99 gCO_2/kWh)
Climate Change	-30%	-54%	-79%	-89%	-81%
Ozone Depletion	-37%	-43%	-50%	-51%	-40%
Particulate Matter Formation	60%	38%	16%	-1%	92%
Acidification	65%	12%	-40%	-41%	-11%
Photochemical Ozone Formation	-4%	-34%	-63%	-74%	-45%
Eutrophication, terrestrial	86%	29%	-29%	-61%	-17%
Eutrophication, freshwater	3458%	1793%	128%	87%	175%
Eutrophication, aquatic	166%	61%	-44%	-63%	-13%
Ionizing Radiation	894%	1112%	1330%	-74%	-9%
Ecotoxicity, freshwater	59%	18%	-24%	-7%	10%
Human toxicity, cancer	80%	40%	-1%	61%	55%
Human toxicity, non cancer	306%	204%	101%	187%	201%
Material Resources	650%	481%	311%	882%	753%
Energy Resources	-41%	-54%	-67%	-97%	-90%
Land Use	282%	187%	91%	-2%	3426%
Water Use	652%	746%	840%	15%	849%

Burden-shifting occurs in land use and eutrophication when switching from a gas condensing heating system to a heat pump. However, further assessment is needed to determine the magnitude of the burden-shift compared to the boundary value. If the shift is low enough, other sectors might be able to efficiently reduce impacts in these two categories and compensate for the burden-shift from switching to heat pumps, for the cause of overall GHG mitigation without pressuring already transgressed planetary boundaries. Ultimately, all sectors in sum need to comply with the planetary boundaries to be sustainable and the strength of heat pumps lies in comparably energy-efficient GHG mitigation [20].

Another criterion besides the immediate environmental impacts that influence the refrigerant selection is the F-Gas regulation [21]. The F-Gas regulation restricts the distribution of high-GWP refrigerants containing fluorine. This restriction can negatively affect the supply and price of refrigerants such as R410A and R32,. Another aspect that has to be considered is the degradation of refrigerants in the atmosphere. The refrigerant R1234yf degrades to TFA within a few weeks [22]. TFA belongs to the group of PFAS chemicals that have been reported to be carcinogenic. Therefore, there are efforts to ban the distribution of PFAS chemicals [23] in the next years which in turn could restrict the option of using R1234yf.

These two criteria are among many that further restrict the possible choice of refrigerants for heat pump applications. In summary, achieving overall sustainable domestic heating will comprise environmental, social, and economic aspects, such as health and refrigerant price.

5. Conclusion

This work performs a life cycle analysis (LCA) for air-to-water heat pumps for use in German residential buildings. Particular focus is put on the influence of refrigerants, which can potentially be used in heat pumps. The refrigerants investigated are the hydrofluorocarbons R410A and R32, the hydrofluoroolefin R1234yf, the hydrocarbons R290, R1270, and R600a, and the inorganic refrigerant R717. The LCA results can be used to estimate which of these refrigerants leads to the lowest environmental impact over the entire life cycle and should be used in heat pumps for residential buildings.

The LCA is divided into four steps according to DIN EN ISO 14040. First, the objective and the scope of the LCA are defined. Then, the life cycle of the heat pump is modeled, consisting of the production and operation of the heat pump and the production and leakage of the refrigerant. Based on these four life cycle phases, a heat pump's environmental impacts are estimated in 16 environmental categories recommended by the ILCD. The LCA results show that the largest share of environmental impacts in the life cycle is due to electricity demand. Therefore, the lowest environmental impacts are achieved by using refrigerants that enable high heat pump efficiency and reduce the required electricity demand. These include R717, R290, and R1270. In contrast, using R410A, R1234yf, and R600a result in the highest environmental impacts, as only low efficiencies are achieved through these refrigerants. Other phases of the life cycle have only a secondary impact. Sensitivity analyses confirm the high significance of the electricity demand for the total environmental impact also until mid-century. Simultaneously, impacts from production become more important with increasingly renewable electricity generation.

One possibility to reduce the environmental impacts due to electricity demand is to increase the efficiency of the heat pump which reduces the electricity demand. A second possibility is reducing the specific environmental impacts of electricity generation by using more renewable energy sources. The expected increase of renewable energy sources in the German electricity mix would decrease the environmental impacts of a heat pump significantly. Therefore, the current electricity mix should not be used for the environmental assessment of a newly installed heat pump. Instead, a possible change in the electricity mix during the heat pump's lifetime should be considered.

Based on the results of the LCA and other selection criteria, such as the F-Gas regulation, a recommendation for action is made, and the use of R290 in residential heat pumps is recommended. The use of R290 leads to low environmental impacts due to its high achievable efficiency. In addition, R290 is non-toxic, has a low GWP, and is already used in heat pumps for residential buildings. The disadvantage of R290 is its high flammability and classification in safety class A3. In addition, DIN EN 378 [3] restricts possible installation sites for R290 heat pumps. If R290 is not possible, alternative refrigerants must be used.

With the environmental impacts of a heat pump determined, an ecological comparison is then made between a heat pump and a gas condensing boiler. As mentioned before, the efficiency of the heat pump and the origin of the purchased electricity significantly influence the environmental impact of a heat pump and, thus, also the ecological comparison. For example, with a SCOP = 3.1 and a predicted increase in the share of renewable energies in the German electricity mix, a heat pump decreases greenhouse gas emissions over the entire life cycle by 54% compared to a gas condensing boiler. However, the environmental impacts can only be reduced in 4 of the 16 environmental categories investigated; in the remaining 12 environmental categories, a heat pump causes higher environmental impacts than gas condensing heating. Therefore, reducing greenhouse gas emissions is achieved by shifting the environmental impact to other categories, i.e., burden shifting. By increasing the heat pump's efficiency, the environmental impacts can be further reduced, but burden-shifting can still not be avoided. Thus, further research has to assess the relevance of the identified burden-shifting, while either way heat pumps offer an opportunity for significant greenhouse gas mitigation.

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