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# Life Cycle Assessment of an Air-Source Heat Pump and a Condensing Gas Boiler Using an Attributional and a Consequential Approach

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**Abstract**

Emissions from heating systems in the building sector significantly contribute to anthropogenic environmental pollution in Germany. Heat pumps are often considered to reduce these pollutions. Therefore, the aim of this study is to compare the environmental impacts of an air-source heat pump with the most commonly used technology, a condensing gas boiler. For this purpose, a comparative life cycle assessment is used. To determine the life cycle inventory of the use phase, an energetic simulation is carried out for both heating systems, with a new single-family house serving as the reference building. The gas boiler is beneficial in 8 out of 11 impact categories. However, the carbon intensity of 76.9 g $CO_2$-eq/MJ heat is 15% higher than for the heat pump. Most environmental impacts for both heating systems occur during operation. The application of the consequential life cycle assessment approach leads to an average reduction of 46% in the environmental impact of the heat pump compared to the attributional approach. In contrast, the gas boiler is only slightly affected by changing the modeling approach. Nevertheless, the heat pump still has higher environmental impacts in 7 impact categories compared to the gas boiler. However, since the reduction of greenhouse gases of the natural gas-fired system is limited, the carbon intensity of the air-source heat pump is 70% lower compared to the condensing gas boiler.



*Keywords:* Life Cycle Assessment, Consequential LCA, Heat Supply, Energy System, Condensing Boiler, Air-Source Heat Pump

## 1. Introduction

Heat is the most crucial form of energy in the German domestic sector, accounting for 90% of the final energy demand within this sector. The heating demand is further divided into 70% for space heating, 14% for domestic hot water (DHW) supply, and 6% for process heat [1]. Due to the strong dependence on fossil fuels, emissions from heating systems account for a significant portion of anthropogenic environmental pollution [2]. Accordingly, 13% of the overall greenhouse gas emissions are caused by the residential sector [3]. In order to meet the German $CO_2$ reduction targets of 80-95% by 2050, it is therefore crucial to transform the heat supply towards renewable energy [4].

With respect to the national Building Energy Act, new residential buildings must be supplied with a minimum rate of renewable heat and the building envelope must meet certain insulation requirements [5]. Heat pumps using renewable energy were thus identified as a key technology for the future heat supply [4]. As a result of financial incentives, the number of heat pumps installed in Germany has grown rapidly during the last 20 years. Although the combustion of natural gas releases a large amount of $CO_2$, natural gas-fired boilers are still the most common heating system used in new buildings [2]. However, in addition to greenhouse gas emissions, other environmental impacts should also be considered when comparing both systems.


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Previous studies have analyzed the environmental impacts of air-source heat pumps (ASHP) [6–8], ground-source heat pumps [9,6,10,8], water-source heat pumps [6], and gas boilers [9,12,6,7,10,8,11]. Those studies used the attributional life cycle assessment (ALCA) method. The second commonly used modeling technique, consequential life cycle assessment (CLCA), analyzes the consequences of decisions. The aim of this study is to determine and compare the environmental impacts of heat pumps, represented by an ASHP, and condensing gas boilers (CGB). For this purpose, an attributional approach is initially applied. To validate the results, consequential modeling is used within a sensitivity analysis. The study is conducted for a typical newly-built single-family house located in Germany.

## 2. Methodology

LCA is a standardized method for examining the environmental burdens of a product system throughout its entire life cycle and is structured in four phases: goal and scope definition, inventory analysis, impact assessment, and interpretation [14,13]. Attributional and consequential modeling are the two general approaches in LCA [15].

### *2.1. Attributional and consequential LCA*

The ALCA methodology considers the immediate physical flows that occur throughout a product's life cycle. This method uses average data for all relevant energy and material inputs within the life cycle [16]. According to the ILCD Handbook, the product system should be expanded to solve multifunctionality. If this is not feasible, environmental impacts of multifunctional processes can be partitioned between the products using physical or economic allocation factors [17]. Often, ALCA studies follow the recycled content approach, also known as the cut-off approach. In this system model, recyclable materials are cut off burden-free from the product system, and thus, environmental burdens resulting from recycling processes are attributed to consumers of secondary materials [18].

CLCA, on the other hand, examines how the relevant physical flows will change in response to a change in demand for the analyzed product [19]. Therefore, consequential models only include unconstrained, marginal suppliers, i.e., suppliers who are able to change their production volume as a consequence of an increase in demand [20,18]. When dealing with multifunctional processes, the consequential modeling approach always avoids allocation by applying substitution [16,19,15,18]. This means that all environmental impacts of an activity are assigned to the reference product, but credits are given for all by-products of the process that can substitute other productions [18].

### *2.2. Goal and scope definition*

The goal of this study is to quantify the environmental impacts of residential space heating and DHW heating in Germany through an ASHP in comparison with a CGB. The functional unit is defined as the thermal energy generated for space heating and hot water for a single-family house in Germany over 20 years. Detailed characteristics of the house and the resulting energy demand are given in Section 3.

Following a cradle-to-grave approach, the study includes the following processes: raw material extraction and processing, product manufacture, system operation, and end-of-life treatments. The environmental impacts associated with the production of the heat distribution system and the storage tank are excluded from the system's boundaries since in this case study both systems use an underfloor heating system and a combined storage tank. Considering these components would thus result in the same environmental impacts, making them redundant. For the heat pump, refrigerant losses occurring during operation are also considered. The lifetime of ASHP and CGB is assumed to be 20 years.

For modeling the background system, the ecoinvent v3.6 database is used. This database supports both types of system modeling, consequential and attributional [20]. The allocation and cutoff by classification system model is used for the ALCA. This database follows the recycled content approach. Contrary to the guidance in the ILCD Handbook, no system expansion is applied in this model and environmental burdens of by-products are allocated based on allocation factors [18]. For the sensitivity analysis, the consequential system model of ecoinvent v3.6 is used for modeling the background system. Although the consequential datasets of this database are kept basic and simplifications are applied, the database fulfills the core concepts of consequential modeling. Thus, marginal suppliers are used instead of average suppliers and the substitution approach avoids allocation [18].

The LCA is performed using SimaPro 9.2 [21] and the CML 2 baseline 2000 v.4.7 life cycle impact assessment method is applied to calculate the following impact categories: Abiotic Depletion Potential (ADP elements and ADP fossil), Acidification Potential (AP), Eutrophication Potential (EP), Fresh Water Aquatic Ecotoxicity Potential (FAETP), Global Warming Potential (GWP), Human Toxicity Potential (HTP), Marine Aquatic Ecotoxicity Potential (MAETP), Ozone Layer Depletion Potential (ODP), Photochemical Oxidation Potential (POCP), and Terrestrial Ecotoxicity Potential (TETP) [22].

## 3. Life cycle inventory analysis

This chapter describes all processes included in the foreground system. To ensure comparability of results, the performance of both heating systems is simulated for a reference building using the Polysun software [23]. In addition, the inventories of the ASHP, CGB, and end-of-life phases are given.

### *3.1. Energy system simulation*

The reference building represents a detached single-family house located in Straubing, southern Germany. It meets the current standard for new buildings in Germany and has a length of 10.7 m, a width of 7 m, and consists of two floors. The total heated living area is 149.8 $m^2$. Table 1 lists the U-values of the reference building's components. In addition, the minimum U-value requirements that new buildings in Germany must meet are specified. At a set room temperature of 19 °C, the resulting space heating demand amounts to 39.1 kWh/($m^2$y), corresponding to 5,858 kWh per year. A DHW demand of 200 l at 50 °C per day with a standard load profile is also considered in the simulation. This results in an energy demand for DHW of 3,473 kWh per year.

Table 1: U-values of the reference building and minimum U-values for new buildings

| | Minimum requirement [5] | Reference building |
|---|---|---|
| | W/($m^2$K) | W/($m^2$K) |
| $U_{floor}$ | 0.35 | 0.24 |
| $U_{roof}$ | 0.20 | 0.14 |
| $U_{wall}$ | 0.28 | 0.20 |
| $U_{window}$ | 1.30 | 0.91 |

Table 2 shows the simulated annual electricity and natural gas consumption for the ASHP system and the CGB scenario. For natural gas, a higher heating value of 11.2 kWh/$m^3$ is assumed for the calculations. Further specifications of the heating systems are given in the next sections.

Table 2: Energy consumption of the considered systems

| Energy consumption | ASHP | CGB |
|---|---|---|
| Electricity consumption [kWh/y] | 2,874 | 21.9 |
| Natural gas consumption [$m^3$/y] | 0 | 907.4 |

### *3.2. Air-source heat pump*

In order to meet the energy demand for space heating and DHW, an ASHP with an output of 5 kW is used. The calculated seasonal performance factor (SPF) amounts to 3.5. Considering the performance of the whole system and, thus, taking into account all heat losses, such as the losses of the buffer tank and the distribution system, the system SPF is 3.26.

Table 3 shows the life cycle inventory of the ASHP production [6]. The heat pump operates with the refrigerant R-134a (1,1,1,2-Tetrafluoroethane). It is assumed that 3% of the refrigerant leaks during the manufacture of the ASHP. In addition, it is taken into account that 6% of the refrigerant is released annually during the operation of the ASHP. Except for refrigerant refilling, the system is considered maintenance-free.

Table 3: Inventory of the ASHP production [6]

| Material | Unit | Amount |
|---|---|---|
| Copper | kg | 36.6 |
| Elastomer | kg | 16 |
| HDPE | kg | 0.5 |
| Low-alloyed steel | kg | 32 |
| Lubricating oil | kg | 2.7 |
| Medium-voltage electricity | MJ | 504 |
| Natural gas | MJ | 1,400 |
| PVC | kg | 1.6 |
| R-134a | kg | 4.9 |
| Reinforcing steel | kg | 120 |

### *3.3. Condensing gas boiler*

A modulating CGB with an output ranging from 1.7 kW to 14 kW is used for the natural gas-fired heating system. The efficiency of the boiler reaches 98.2% when considering the higher heating value of natural gas. With respect to the entire heating system, the efficiency amounts to 88.7%.

Table 4 summarizes the materials and energy requirements for the production phase of the CGB [11]. The emissions occurring during the use phase, and thus resulting from the combustion of natural gas, are taken from [24]. The $CO_2$ emissions due to combustion were determined using stoichiometric calculations, resulting in 61.38 g $CO_2$/MJ heat. For the sake of simplicity, the gas-fired heating system is assumed to be maintenance-free.

Table 4: Inventory of the CGB production [11]

| Material | Unit | Amount |
|---|---|---|
| ABS | kg | 1.171 |
| Aluminum | kg | 1.905 |
| Brass | kg | 3.215 |
| Copper | kg | 2.290 |
| Electronic components | kg | 0.248 |
| EPDM | kg | 0.064 |
| Low-alloyed steel | kg | 22.879 |
| Medium-voltage electricity | MJ | 79.9 |
| Natural gas | MJ | 116.6 |
| PVC | kg | 0.005 |
| Silicone | kg | 0.115 |
| Stainless steel | kg | 6.736 |
| Wiring | kg | 0.372 |

### *3.4. End of life*

A lifetime of 20 years is assumed for both heating systems. Current recycling rates of the EU-28 are used to model the end-of-life phase of metals (see Table 5) [25]. The remaining part of the metals is landfilled. It is assumed that all plastic components are incinerated at their end of life.

Table 5: End-of-life recycling rates in the EU-28 [25]

| Material | End-of-life recycling rate [%] |
|---|---|
| Aluminum | 69 |
| Copper | 61 |
| Steel | 75 |

Regarding the refrigerant, the ecoinvent database treats the end-of-life phase differently in the two modeling approaches. In the consequential version, 90% of the refrigerant is reclaimed and 10% is incinerated [26]. Whereas the attributional model assumes that 27% is reclaimed, 23% is incinerated, and 50% is vented to air [27].

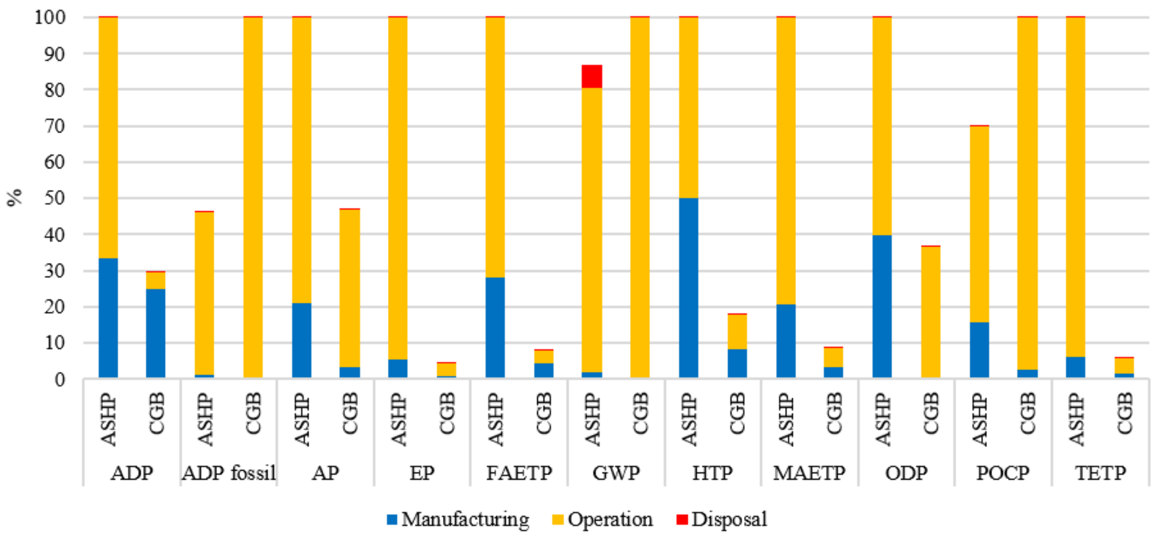


Fig. 1: Impact assessment results using attributional modeling

## 4. Results and discussion

To analyze the results, the impacts are assigned to the respective phases of the product life cycle, which are manufacturing, operation, and disposal. For the ASHP system, the operation phase also includes the environmental impacts of refrigerant refilling. Fig. 1 shows the relative environmental impacts associated with providing heat for space heating and DHW for the reference building. Overall, the application of the CGB is beneficial in 8 out of 11 impact categories. In contrast, the ASHP has less impact in 3 categories: ADP fossil, GWP, and POCP.

With respect to the ASHP, the operation phase accounts for 78% of all environmental impacts on average, whereas manufacturing is responsible for 21%. The impact of the system's end of life is negligible. Except for GWP and ODP, emissions released during ASHP operation are mainly attributed to the electricity demand when using electricity generated with the currently available generation structure in Germany according to ecoinvent. While 81% of the GWP also originates from electricity generation, 19% is associated with refrigerant leakage, as R-134a has a GWP of 1,300 [28] and, thus, even small losses have a large impact. With respect to the ODP, 78% of the emissions are associated with the production of the leaked refrigerant. Although R-134a has no ODP, small amounts of HCFC-124 and CFC-113 are emitted during the production of R-134a. These two intermediate products have depleting effects on the ozone layer [28]. Only in the impact categories ODP and HTP does the production phase have a larger impact than the operation of the ASHP. While for the ODP this is also due to the production of the refrigerant, copper extraction has the largest effect on HTP.

With regards to the CGB, its operation causes 75% of all environmental impacts on average. The remaining 25% are attributed to the production phase. During operation, the supply of natural gas has the largest impact in 10 categories. The only exception to this is the GWP, as 80% of the $CO_2$-equivalents emissions originate from natural gas combustion, resulting in total greenhouse gas emissions of 76.9 g $CO_2$-eq/MJ heat. Only for ADP and FAETP does the manufacturing phase contribute more than the operation of the CGB. In the ADP impact category, this is almost entirely associated with the production of brass. The FAETP mainly results from the use of copper.

Overall, the use of a CGB is currently beneficial in most impact categories. However, the majority of emissions from both systems are associated with the operation phase. While the future environmental impacts of the CGB can be reduced mainly through efficiency improvements, the impacts of the ASHP can be additionally improved through decarbonization of electricity [8].

To validate these results, a sensitivity analysis is performed by applying the consequential modeling approach (Fig. 2). In the diagram, the positive values represent the final results. On the other hand, the negative values represent credits that have already been deducted for recycled materials that can substitute other processes. Applying the consequential approach, the ASHP has higher environmental impacts in 7 impact categories. However, with respect to the ADP fossil, AP, GWP, and POCP, the ASHP is advantageous compared to the CGB.

In this approach, operating the ASHP causes 64% of the environmental impacts and manufacturing is responsible for 36%. Similar to the attributional model, electricity is the largest contributor to emissions during operation in 9 impact categories. Using the German marginal electricity supply mix, the supply of electricity causes only 50% of the operation's greenhouse gas emissions. The remaining emissions originate from refrigerant leakage. Including all life cycle stages, the ASHP emits 24.4 g $CO_2$-eq/MJ heat. In terms of HTP, POCP, and AP, the production phase accounts for more environmental impacts than the operation phase.

With regard to the CGB, 68% of the emissions originate from the operation and 32% from production, and thus, the proportions changed only slightly compared to attributional modeling. The supply of natural gas is still the most important aspect influencing the operation of the CGB. In addition, 80% of the GWP is still assigned to the combustion of natural gas.

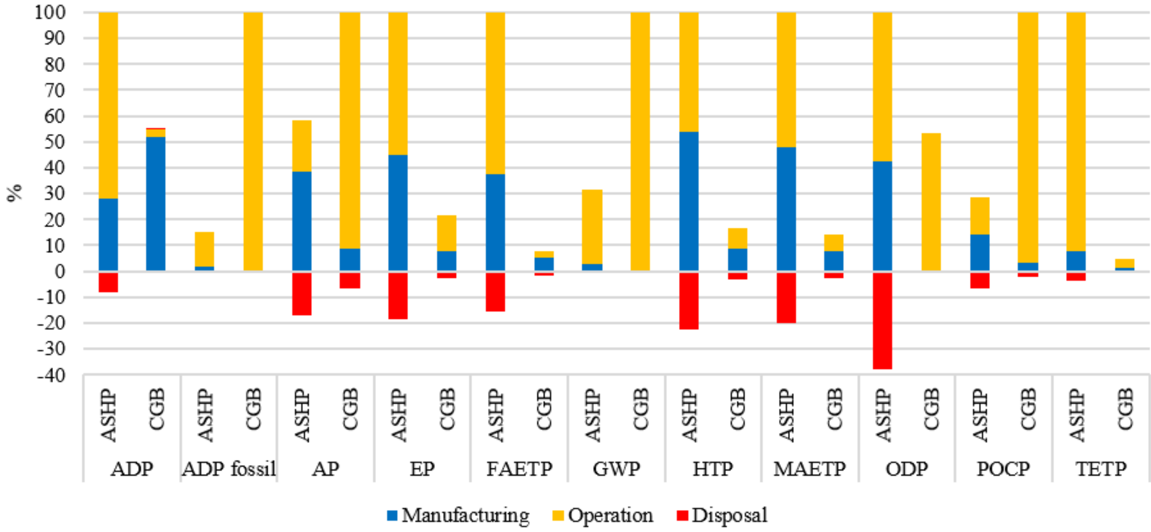


Fig. 2: Impact assessment results using consequential modeling

In the ADP, HTP, and MAETP categories, manufacturing has the greatest influence. While this can be attributed to brass production for ADP, copper extraction mainly affects HTP, FAETP, and MAETP.

As can be seen in Fig. 3, the general environmental performance is independent of the modeling approach. Under attributional modeling, the gas boiler has lower impacts in 8 impact categories. When using the consequential approach, this only changes for the AP, and thus, the gas boiler is still advantageous in 7 categories. However, applying consequential modeling for assessing environmental impacts of the ASHP leads to an average reduction of 43% among all impact categories. The largest differences occur for the EP (86%), AP (75%), ADP fossil (66%), and GWP (63%). Among these categories, the use of the marginal instead of the average electricity supply mix is the main driver for reductions. The electricity mix of the attributional approach reflects the current average of German electricity generation, which is characterized by high consumption of fossil fuels as indicated by a GWP of 575 g $CO_2$-eq/$kWh_{el}$. In contrast, the electricity mix of the consequential model reflects the implications of changes in electricity demand on the installation of new power generation capacities. The marginal electricity mixes of the ecoinvent database are based on energy forecasts of national and international authorities [29]. Therefore, the German marginal electricity supply mix originates from a higher proportion of renewable energy as represented by a GWP of 133 g $CO_2$-eq/$kWh_{el}$.

Another key factor for the different results of the two modeling approaches is crediting for substitutions, which has large effects on the ODP of the ASHP. In the consequential model, 90% of the refrigerant is reclaimed during disposal, leading to lower impacts compared to the attributional model.

With regard to the gas boiler, the differences between the two LCA approaches are lower, resulting in an average reduction of 6% using the consequential modeling. The main reason for this is that the impacts of the CGB are dominated by the supply and combustion of natural gas. Unlike the electricity mix, the environmental impacts of marginal natural gas

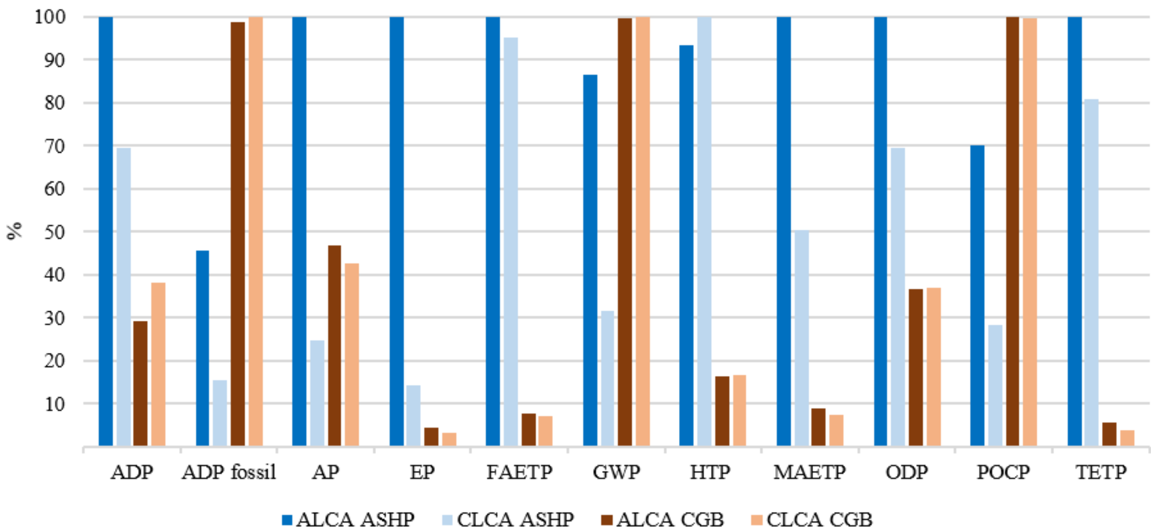


Fig. 3: Relative impact assessment results of the different modeling approaches

suppliers are less different from the impacts of current average suppliers.

According to Steubing et al., the largest difference in the results of attributional and consequential ecoinvent datasets originates from using marginal instead of average suppliers [30]. Therefore, for a more detailed CLCA, the focus should be on the identification of marginal suppliers. When interpreting the results of this study, it is important to note that, contrary to the ILCD Handbook, substitution was not applied in the attributional model for solving multifunctionalities.

## 5. Conclusion

This paper presents the results of a comparative LCA of an ASHP and a CGB in Germany. The ASHP has higher environmental impacts in 8 out of 11 impact categories. These are to 78% attributable to the operation, and thus mainly to the electricity consumption of the ASHP. In contrast, the emissions of the CGB primarily originate from the supply and combustion of natural gas.

Within a sensitivity analysis, a CLCA is performed, and thus, the consequences of a change in demand are analyzed. Although consequential modeling substantially reduces the absolute LCA results of the ASHP, it still has higher environmental impacts in 7 impact categories. Thus, the general trend of environmental impacts of the ASHP and CGB is independent of the modeling approach. However, the GWP of the ASHP is only one-third of the GWP of the CGB.

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