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Sustainable Heating Systems: Ecological Assessments of Various Heat Pump Solutions in Single-Family Houses

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Abstract. This contribution examines the ecological impacts of various heat pump configurations employed in newly constructed single-family homes in Germany. Four key technologies are assessed: air source heat pumps (ASHP), ASHP with solar thermal collectors (ST), brine-water heat pumps (BWHP) paired with photovoltaic-thermal (PVT) collectors, and ground source heat pumps (GSHP). Employing life cycle assessment (LCA), the environmental impacts, focusing specifically on climate change and resource use impacts, are investigated. The findings reveal that the GSHP demonstrates the lowest carbon footprint at 0.082 kg CO_2-eq./kWh_{th}, whereas the BWHP+PVT configuration presents the highest at 0.095 kg CO_2-eq./kWh_{th}. A significant observation is that the electricity sourced from the grid substantially influences climate change impacts across all technologies. Furthermore, sensitivity analyses indicate that accounting for environmental credits from excess electricity generated by PVT systems considerably lowers the overall carbon footprint. By investigating these heating technologies, this paper aims to provide insights into the environmental performance of different heat pump configurations for informed decision-making in the transition towards sustainable energy systems, highlighting the necessity for reliable data and standardized frameworks for ecological assessments.

Keywords: Heat Pump Systems, Life Cycle Assessment, Renewable Energy

1. Introduction

Both the threat of climate change and growing uncertainties in resource supply require a comprehensive transformation across all sectors. Currently, almost one third of Germany's greenhouse gas (GHG) emissions originate from the energy sector [1]. The defossilization of the energy consumption through the comprehensive expansion of renewable energies is a key pillar in the "Energiewende". To further promote investments in the expansion of renewable energies, especially in the heating sector, amendments to the Building Energy Act (GEG) came into effect on January 1, 2024. For the installation of heating systems in new buildings within new construction areas, the GEG requires a minimum share of 65% of the heat demand to be covered by renewable sources. For existing buildings, corresponding exceptions and transitional regulations still apply.

Currently, heating technologies are primarily selected based on their economic viability. However, one of the main drivers behind the heating transition is the increasing threat of climate change, therefore the comparison of the ecological footprint of available heating technologies is essential. At the same time, the rapid deployment of sustainable heating technologies without proper resource management could lead to raw material bottlenecks, hindering the decarbonization of the heating sector. As of now, there is still a lack of reliable data and uniform frameworks for comprehensive economic and ecological assessments. To make a sustainable choice, reliable and fair comparisons across different heating technologies must be available.

Renewable energies in the field of heat supply encompass a wide range of technologies. Currently, renewable energies account for about 17.7% of Germany's heat demand [2]. The majority of this is provided by various forms of biomass (38%), though this share is steadily decreasing. This is connected to the expansion of heat pumps over the past five years (especially air-water heat pumps) [3]. Other renewable heat supply technologies have also seen increases. Approximately 5% of heat demand was covered by solar thermal collectors in the past year [2]. While all these technologies have environmental impacts during their production and disposal phases, they differ significantly during the use-phase. The use of solar thermal collectors causes no direct emissions, while the emissions attributed to the use of a heat pump mainly result from the electricity mix and system efficiency. Biomass, as a third example, causes direct emissions during the combustion process. However, these are currently classified as biogenic emissions (non-fossil). Therefore, biomass is considered a carbon-neutral energy source in terms of balance. As the (potential) environmental impacts of various renewable energy sources differ, so do the costs and returns over their respective system lifetimes.

A common methodology for quantifying and assessing potential environmental impacts is life cycle assessment (LCA). Its fundamental approach is defined in the two ISO standards DIN EN ISO 14040 and 14044 [4, 5]. At the same time, the standards allow for considerable flexibility in individual decisions, which can limit or even prevent the comparability of LCA results. Variations in system boundaries, functional units, and evaluation methods play a crucial role in this. While there are further recommendations and guidelines for standardizing ecological assessments and thus enhancing comparability for individual technologies, these mainly focus on single technologies and are not designed to enable comparisons across multiple technologies. Due to the variety of technologies, a comprehensive comparison based on ecological and economic aspects is currently not possible. As a result, investors lack reliable guidelines for making sustainable decisions.

The German project “Effizientes Heizen” (*Efficient Heating*) aims to close this research gap. A comprehensive assessment approach is developed to evaluate and compare various heating technologies based on both ecological and economic performance, with a focus on the application in residential buildings. This contribution in particular focuses on the ecological assessment and the comparison of different configurations of renewable heating systems including a heat pump in single-family houses.

2. Methodology

A central aspect of the comparability of LCA results is the uniform definition of system boundaries across the different technologies. To create maximum value for users, only the heating system and its components are considered. Potential renovations of buildings (e.g., additional insulation) or the distribution system (radiators) are not considered in this comparison. To further enhance the comparability of the results, the consumption side is standardized using representative standard load profiles [6]. All considered heating technologies are designed to cover the heat demand of the reference buildings at all times.

In line with ecological assessment approaches in the building sector, modelling and evaluation are conducted according to EN15804+A2. The applied system-model is the "cut-off" approach, where no credits are awarded due to potential recycling efforts at the end-of-life. To enhance transparency, there is the possibility to separately list environmental benefits or potential burdens, that go beyond the system boundaries, such as the recyclability of products or the additional electricity production from the PVT collector. In addition to methodological aspects, technological parameters must also be standardized for a comprehensive and fair comparison. This includes the lifespan of the heating systems and individual components, efficiency, degradation rates and patterns, installation location, applied disposal scenarios, and the electricity mix used (see also [7]).

The heating technologies considered are designed in accordance with the GEG and selected based on their market relevance. Specifically, the following technologies are evaluated in the project:

- Air source heat pump
- Air source heat pump with solar thermal
- Brine-Water heat pump with PVT collector as a heat source
- Ground source heat pump
- Air source heat pump with gas condensing boiler *(note: not detailed in this paper)*
- Pellet heating system *(note: not detailed in this paper)*

2.1 System boundaries and Functional unit

While in the project “Effizientes Heizen”, both single-family and multi-family homes are examined, this contribution focuses on the application in a newly built single-family house. The functional unit is set to 1 kWh of heat supplied and the system boundaries include the respective heating system, while excluding the heat distribution in the building (e.g., radiators). In this study, the production and the use phase of the heating systems are considered, while the end-of-life is not yet included. The individual lifetimes of the components are taken into account. The heating systems include additional auxiliary components such as hot water storage tanks, piping, or additional pumps. These components are standardized for all systems and only varied in size, where applicable. The heat demand curve was modeled based on the reference location of Potsdam, utilizing weather data from 2015 [6].

Additionally, it is assumed, that part of the roof area is covered in either solar thermal collectors (ST), PVT, PV or a combination of those, depending on the system configuration. Since the ST only provides thermal energy, they are fully accounted for in the LCA of the heating system. The PV modules provide electricity that is used partially to power the heat pump. Since the time of the production of the electricity does not necessarily match the time of the electricity consumption by the heat pump, excess electricity is fed into the grid and at other times, electricity from the grid is used to power the heat pump. Therefore both, the PV-electricity and the grid electricity are considered in the use phase of the heating system. PVT modules provide both, useful heat and electricity. The heat is provided to the heat pump, while the electricity is only partly used to produce heat. As for the PV, also for the PVT excess electricity is fed into the grid. However, there is no common or established practice to distinguish between the heat and the electricity production within the LCA. In this assessment, the PVT collector is seen as a part of the heating system and therefore it is fully considered in the LCA (in accordance with the ST). However, a more detailed assessment is conducted on the influence of accounting for the benefits of the excess electricity production in the form of a sensitivity analysis.

Air source heat pump (ASHP): The first of the investigated heating system consists of a 4.88 kWp (A-7/W35) ASHP, with propane (R290) as the refrigerant. It is combined with a 10 kWp rooftop PV system consisting of monocrystalline silicon modules. For storage, a 150 l buffer storage tank and a 250 l domestic hot water storage tank are installed. To cover the annual heat demand of 10.8 MWh_{th} (see also [6]), about 3.2 MWh_{el} of electricity are required. 71% of this electricity is sourced from the grid, while 29% is taken from the rooftop PV system. The energetic simulations have been carried out using PolySun.

Air source heat pump with solar thermal collectors (ASHP + ST): The second system is a combination of an ASHP with a solar thermal system. Both technologies feed into the same storage. The buffer storage tank is the same size as in the first system, while the domestic hot water storage tank has a volume of 400 l in this set up. The ST is sufficient to cover the hot water demand during the summer months. The ST covers 6 m² of the roof area, so that the PV system is downsized, compared to the previous system to 8.8 kWp. The addition of the ST results in a reduced electricity consumption in the use phase of 2.8 MWh_{el}. However, only 20% of this electricity is sourced directly from the rooftop PV system, while the remaining 80% are taken from the grid.

Brine-Water heat pump with PVT collectors (BWHP + PVT): The third system to be investigated in this study is a BWHP that uses PVT as a heat source. The considered heat pump has a heating capacity of 4.88 kWp (B0/W35) with propane as the refrigerant. The PVT system covers a rooftop area of 14.5 m² and has a capacity of up to 3 kWp. Additionally, a 7.4 kWp PV system is installed. 32% of the annual electricity demand of 3.1 MWh_{el} is covered by PV (23%) and PVT (9%) electricity. Additionally, each year, 2.6 MWh_{el} of electricity is produced by the PVT system to be used for other applications. The buffer storage tank has a volume of 150 l, while the storage tank for domestic hot water has a volume of 250 l.

Ground source heat pump (GSHP): The fourth and last system considered here is a GSHP. The heat pump itself as well as the storage tanks are assumed to be the same as in the BWHP+PVT configuration. The ground probe that is used as a heat source is assumed to be 85 m long. In accordance with the ASHP, a 10 kWp PV rooftop system is included as well as a 150 l buffer storage tank and a 250 l domestic hot water storage tank. In this system, 32% of the required annual electricity (2.7 MWh_{el}) is covered by the rooftop PV.

2.2 Life Cycle Inventory

The data requirements are primarily met through the collection of primary data from project partners. This data is supplemented with values from the ecoinvent database [8] and information from scientific literature to fill data gaps. Most components have been modelled based on its material composition, since no reliable data was available on specific production steps. Whenever possible, the energy consumption in the production phase of the components has been included. The LCI data for the heat pumps has been collected by investigating material compositions and weighing of components of state-of-the-art heat pumps. Therefore, the energy consumption for the production phase of the heat pumps is not included in the dataset. The data for the ST and PVT collectors has been provided by project partners.

Table 1. *German Electricity Grid Mix in 2024. Relative shares calculated from the data provided by the Fraunhofer ISE Energy Charts [9].*

Source	Share in 2024
Hydro Run-of-River	4%
Biomass	9%
Fossil brown coal / lignite	17%
Fossil coal-derived gas	1%
Fossil hard coal	6%
Fossil oil	1%
Fossil gas	11%
Waste renewable	1%
Waste non-renewable	1%
Wind offshore	6%
Wind onshore	27%
Solar EEG grid feed-in	14%

The ground probe has been taken from Kägi et al. [10]. This source was chosen since it includes the fuel consumption for the installation of the probe. The data for the storage tanks were compiled within the project to represent a market average. The LCI for additional pumps and the expansion vessel are taken from the ecoinvent database and the pipes are assumed to be made of copper and 10 m have been assumed for each of the systems. The LCI for the state-of-the-art rooftop PV-system is taken from literature [11] and scaled according to the system configuration. The grid mix for the electricity consumption in the use phase has been modelled according to the average German grid mix for 2024 as provided in the Energy Charts by the Fraunhofer ISE [9] (see *Table 1*). The investigated timeframe is 25 years, while the individual lifetimes of the system components are considered. The modelling is conducted in the software SimaPro and ecoinvent is used for background processes.

3. Results

3.1 Overview

The environmental impacts of the described systems are investigated using the impact assessment methodology EN15804+A2. In this study, the focus is on the impacts in the category *climate change*, as well as *resource use, minerals and metals*. All impacts are presented in relation to the chosen functional unit of 1 kWh of thermal energy supplied to the building (if not specified otherwise).

Figure 1 provides an initial overview of the comparison of the heating systems investigated. The impacts in the category climate change range from 0.082 kg CO_2-eq./kWh_{th} for the GSHP to 0.095 kg CO_2-eq./kWh_{th} for the BWHP+PVT. The ASHP+ST has a slightly lower climate change impact than the ASHP with 0.089 kg CO_2-eq./kWh_{th} compared to 0.091 kg CO_2-eq./kWh_{th}, respectively. When looking at the resource use of minerals and metals, the comparison changes. While the GSHP shows the lowest and the BWHP+PVT the highest impacts also in this category, the ASHP performs better than the ASHP+ST which has a slightly higher impact. Overall, the relative differences in the impacts in the category resource use, minerals and metals are larger than in the category climate change.

The electricity consumption during the use phase has a significant influence on the climate change impacts in all systems, while the production phase is much more dominant when looking at the resource consumption. The electricity grid mix has a climate change impact of 0.401 kg CO_2-eq./kWh_{el} while the PV electricity entails a carbon footprint of 0.030 kg CO_2-eq./kWh_{el}.

ASHP: Taking a closer look at the ASHP, a carbon footprint of 0.091 kg CO_2-eq./kWh_{th} has been calculated. 91% of these impacts are due to the electricity consumption from the grid in the use phase of the heat pump, followed by 6% that originate from the production phase, and 3% of the impacts from the self-consumed electricity from the rooftop PV plant. The impacts in this category are dominated by the use of fossil fuels. This applies to the electricity consumption in the use phase, as well as the production of material for the components of the heating system. In the resource use category, the production phase of the system is dominant. 72% of the impacts in this category originate from the use of materials within the system's components. Resource requirements for the provision of electricity contribute 17% and 11% for the PV electricity and the electricity from the grid mix, respectively. The resource use impacts are largely dominated by the use of copper in the heat pump and additional piping.

ASHP+ST: The carbon footprint of the heat provided can be slightly lowered by adding a solar thermal system to the ASHP. The calculated impacts in the category climate change for the ASHP+ST are 0.089 kg CO_2-eq./kWh_{th}. For the category climate change, the additional production impacts due to the production of the solar thermal collectors are offset by the reduction in electricity consumption. This is not the case when looking at the resource use impacts. Compared to the ASHP, the production phase impacts increase by 22%. The impacts per kWhth in the resource use category increase by 11% when both the production and the use phase are taken into account.

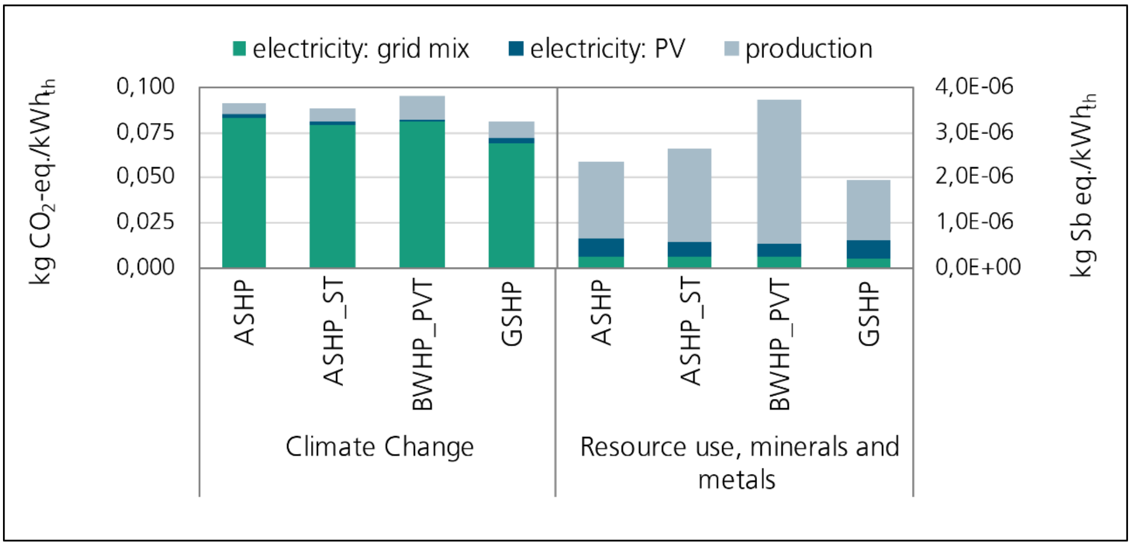

Figure 1. *Comparison of the environmental impacts of the investigated heating systems by impact category. In the use phase, the 2024 German electricity mix is assumed, and the individual lifetimes of system components are considered. For the BWHP+PVT system no credits are awarded for the additional useful electricity production. FU = 1 kWh$_{th}$ of heat provided to the building. Method: EN15804+A2. Note: The impacts can only be compared within the same impact category, as they are given in different units.*

BWHP+PVT: This system exhibits the highest carbon footprint in this comparison with 0.095 kg CO_2-eq./kWh$_{th}$. While the impacts for the electricity consumption from both PV and the grid are lower than for the ASHP and the ASHP+ST, the impacts for the production phase are significantly higher. This is on the one hand due to the impacts resulting from the production of the PVT system. However, it must be noted that also methodological aspects regarding allocation distorts this comparison to some extent. As previously mentioned, there is no unified approach to the allocation of impacts to the produced heat and electricity in a PVT module. Since only part of the electricity produced by the PVT collectors is used for the heating system, there is an additional benefit of excess electricity that can be used for other applications. In this first assessment no allocation procedure or environmental credits have been included. This means, that the excess electricity leaves the system boundaries burden-free. Therefore, it could be argued that the impacts are overestimated in this case. To quantify the influence of potential credits on the carbon footprint as well as the resource use, a sensitivity analysis is conducted in the following chapter.

GSHP: Finally, the assessment of the GSHP shows the lowest impacts in the two categories investigated for this comparison. The carbon footprint of 0.082 kg CO_2-eq./kWh$_{th}$ is, again, largely due to the electricity consumption from the grid in the use phase with a contribution of 85%. The production phase (including the installation of the ground probe) contributes about 12% to the climate change impacts, while the self-consumption from the PV-rooftop plant makes up about 3% of the impacts. As for the previous systems, the resource use impacts originate from the production phase with 68%.

3.2 Sensitivity Analysis

Influence of the assessment period: In the assessment, it has been assumed that all system components are used until they fulfill their individual lifetimes, independent of the assessment period. Components whose lifetime exceed the assessment period of 25 years are only accounted for partially. However, it is noteworthy that when a heating system is replaced, additional components are often replaced as well, even if they have not yet reached their technical end of life. To quantify the impact of this methodological assumption, a sensitivity analysis was conducted with a fixed assessment period of 25 years, in which all components are considered

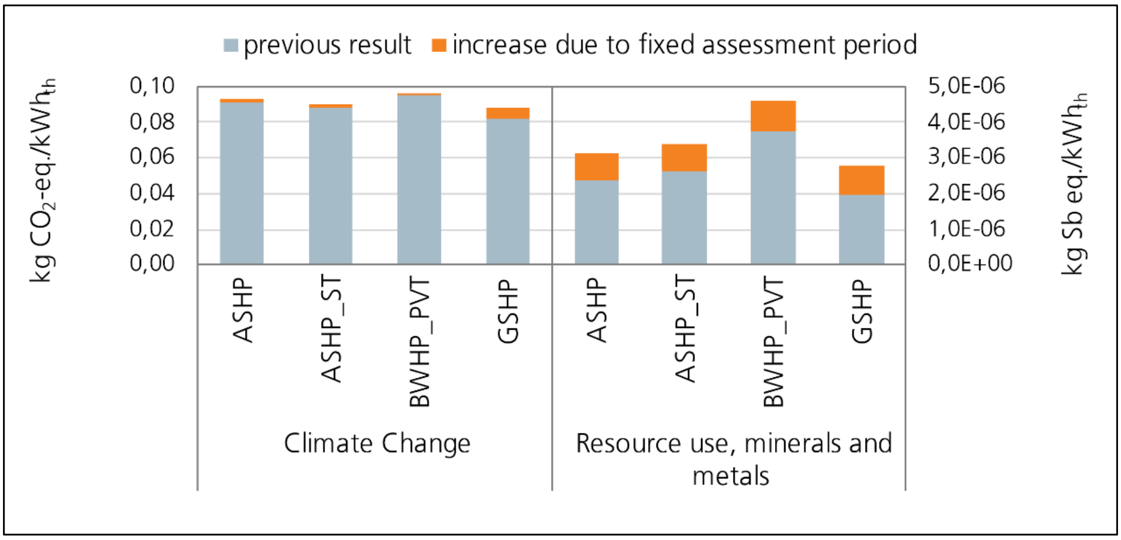

Figure 2. *Sensitivity analysis: Fixed assessment period. Comparison of the environmental impacts of the investigated heating systems by impact category. In the use phase, the 2024 German electricity mix is assumed. For the BWHP+PVT system no credits are awarded for the additional useful electricity production. FU = 1 kWh_{th} of heat provided to the building. Method: EN15804+A2. Note: The impacts can only be compared within the same impact category, as they are given in different units.*

in full, regardless of their potential continued use beyond this timeframe (see Figure 2). The results show only a slight increase (+2%) in the climate change impacts per FU for the ASHP, the ASHP+ST and the BWHP+PVT system. For the GSHP the climate change impacts increase by 8%. Looking at the resource consumption, the influence is much more significant. By fixing the assessment period the impacts are increased by 22% to 42%. This increase in impacts can be traced back to the production phase impacts. In the primary assessment in this study, all components are expected to be used until the end of their individual lifetimes, even if this exceeds the timeframe of 25 years. In the LCA this implies that their production phase impacts are distributed evenly over their lifetimes, leading to some impacts being allocated outside this considered timeframe. Consequently, this share of impacts is excluded from this assessment. When the assessment period is now fixed, all impacts originating from the production phase are allocated within the considered timeframe, increasing the considered impacts. Since the distribution of the production phase impacts is the driver for the increase in impacts per FU, the category resource use is more significantly affected than the climate change impacts. Notably, the impacts for the GSHP system increase the most in this comparison. This is due to the fact that the ground probe is expected to have a lifetime of 50 years. While in the primary assessment, only 50% of the production impacts were considered, in the sensitivity analysis the full impacts of the ground probe are accounted for. The impacts for the use phase of the system (electricity consumption) are not affected by this sensitivity analysis.

Electricity mix projection 2045: A second sensitivity analysis is conducted on the electricity consumption mix in the use phase (see Figure 3). For this, the electricity mix projected by Brandes et al. [12] for the year 2045 is taken for the electricity grid mix. The continuous decarbonization through the deployment of renewable energies leads to a significantly lower carbon footprint of 0.087 kg CO_2-eq./kWh_{el} in the year 2045. Consequently, the carbon footprint of the heat provided by the investigated heat pump systems can be expected to decrease as well. When the 2045-gird mix is used, the carbon footprint per FU decreases to 0.026 kg CO_2-eq./kWh_{th} to 0.032 kg CO_2-eq./kWh_{th} for all systems. This marks a reduction in the carbon footprint by 67% to 71% compared to the utilization of the 2024 electricity grid mix. Looking at the resource consumption, a slight increase in impacts per FU can be observed, ranging between 5% and 8% for all investigated systems. This increase is attributed to the higher material demand per kWh of renewable energy technologies compared to fossil energy sources. Since

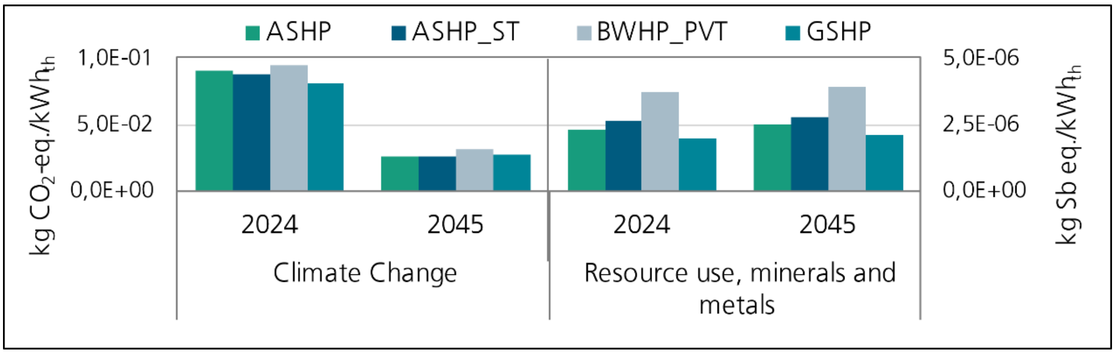

***Figure 3**. Sensitivity analysis: Electricity grid mix projection for 2045. Comparison of the environmental impacts of the investigated heating systems by reference year for the electricity grid mix used and impact category. The individual lifetimes of system components are considered. For the BWHP+PVT system no credits are awarded for the additional useful electricity production. FU = 1 kWh_{th} of heat provided to the building. Method: EN15804+A2. Note: The impacts can only be compared within the same impact category, as they are given in different units.*

electricity consumption contributes only minimally to resource use impacts in these systems, its effect on the overall results remains limited. However, this trade-off cannot be neglected. It underscores the necessity for the efficient use of resources in the transition to a renewable electricity supply.

Credits for PVT electricity: Finally, the third sensitivity analysis is conducted to consider credits for the excess electricity produced by the PVT system (see Figure 4). There is currently no standardized approach for the allocation of the environmental impacts of a PVT collector between the produced heat and electricity. In this analysis, all environmental impacts have thus far been attributed to the heating system. The additional electricity produced by the PVT panel leaves the system boundaries burden-free. This approach therefore does not account for the additional benefits derived from the excess electricity production. An alternative to allocation is the avoided burden approach, which allows for the attribution of credits. The reasoning behind this approach is that the electricity generated by the PVT collector and fed into the grid avoids the corresponding amount of electricity production from other sources. To implement this approach, a reference electricity source must be defined to serve as the basis for the credits. For this sensitivity analysis, the electricity production from PV modules is taken as the reference. By choosing PV as the reference, the goal was to reflect the real impacts of the electric part of the PVT collector as closely as possible, to ensure that realistic environmental credits are awarded. By considering these credits, the climate change impacts for the

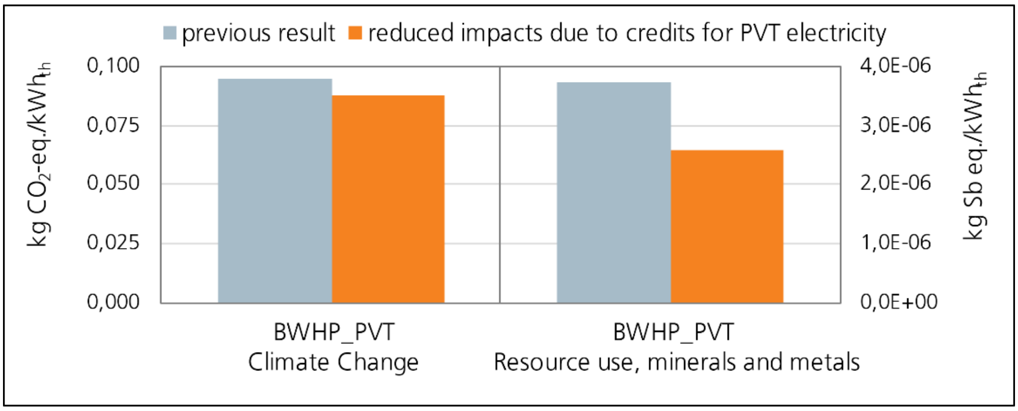

***Figure 4.** Sensitivity analysis: Environmental Credits for excess PVT electricity generation. Comparison of the environmental impacts of the investigated heating systems by impact category. FU = 1 kWh_{th} of heat provided to the building. Method: EN15804+A2. Note: The impacts can only be compared within the same impact category, as they are given in different units.*

BWHP+PVT system decrease by about 8% to 0.087 kg CO_2-eq./kWh_{th}. The impacts in the resource use category are reduced by more than 30% due to the consideration of the credits.

4. Discussion

The assessment provides insights into the ecological impacts that are attributable to different heat pump configurations for newly built single-family houses. The carbon footprint for the investigated systems ranges from 0.082 kg CO_2-eq./kWh_{th} to 0.095 kg CO_2-eq./kWh_{th}. For all heating systems, the main driver of climate change impacts is the electricity that is sourced from the grid in the use phase, contributing between 85% and 91%, while the self-consumption of PV electricity from the rooftop plant contributes 2% to 3%. Additional research suggests that the carbon footprint of the electricity that is sourced from the grid may be underestimated when an annual grid mix is applied, since heat pumps especially require electricity in the winter months, when the share of fossil electricity in the grid mix tends to be higher than in the annual average [13]. Simultaneously, the on-going decarbonization of the electricity mix in the coming years will significantly lower the carbon footprint of heat that is provided by heat pumps in the years to come (see also [14]). The assessment clearly shows, that decarbonization of the electricity that is used in the operation of the heat pump has the largest lever to lower the carbon footprint of the supplied heat. However, the conducted sensitivity analysis also shows the increase in impacts in the category resource use, minerals and metals. This trade-off highlights the importance of comprehensive transformations that consider the entire context. Sustainable material sourcing and the transition to a circular economy are crucial for minimizing environmental impacts and mitigating trade-offs in the energy transition.

The importance of the responsible and efficient use of resources can also be seen in the sensitivity analysis investigating the influence of a fixed assessment period. This study considers components according to their individual lifetimes, with a 25-year assessment period. Not all components, however, need to be replaced exactly at this interval. Some may require earlier replacement, thus remaining functional beyond the 25-year timeframe. Additionally, certain components inherent lifetimes exceeding 25 years. It is reasonable to assert that components might be replaced before reaching their end-of-life due to maintenance activities on the system or the transition to a different energy source. Consequently, a sensitivity analysis was performed to explore the assumption that the entire heating system is replaced after 25 years. The results show that this assumption significantly affects the impacts in the category resource use. To minimize impacts, it is crucial to utilize components until their end-of-life. While this assessment assumes identical replacements, real-world technological advancements could reduce the impacts associated with such replacements in the future.

The impacts of the production phase are the highest for the BWHP+PVT system, contributing 13% to the carbon footprint of the provided heat. For the GSHP, the production phase impacts contribute 12% to the overall carbon footprint. Here, the installation of the ground probe requires fossil fuels. For the ASHP and the ASHP+ST system the production phase of the system contributes comparatively low shares with 6% and 8%, respectively. Without the attribution of credits, the BWHP+PVT system shows the highest impacts in this category. The sensitivity analysis shows that by employing the avoided burden approach and awarding environmental credits for the excess electricity that is fed into the grid, the carbon footprint of the provided heat can be reduced by 8% to 0.088 kg CO_2-eq./kWh_{th}. This way, the attributed carbon footprint of the provided heat is lower than for the ASHP and the ASHP+ST system. However, it must be noted that this is only a theoretical credit, to account for useful by-products. The excess electricity that is fed into the grid no longer leaves the system boundaries burden-free, but with a carbon footprint of 0.030 kg CO_2-eq./kWh_{el}, since this is the carbon footprint of the PV electricity that was chosen as the reference. Awarded credits and allocation procedures must always be transparent, and the chosen reference must be clearly defined.

As mentioned previously, this assessment only covers the production and the use phase of the systems. The end-of-life has not been considered in this study. While it is expected that the production and use phase cause the majority of environmental impacts, the consideration of the end-of-life phase is crucial for a complete and comprehensive comparison of the environmental impacts of the system. Further, the assessment focuses on the environmental impacts of the heating systems, without considering economic aspects. The economic assessment for these systems is conducted by the IGTE University of Stuttgart [15].

To ensure comparability among the systems, the demand side has been standardized by establishing a reference building along with an associated heat demand curve. Since this approach aims to represent an average building, it may not be universally applicable to all newly constructed single-family homes. The same consideration applies to the building's location, which is assumed to be Potsdam. The heat demand curve was modeled weather data from 2015 [6]. The definition and scaling of system components were conducted in accordance with the pre-defined heat demand curve. While the selected components are intended to reflect a market average, the transferability of the model and consequently the obtained results must be evaluated on a case-by-case basis, as varying heat demand curves may require different system configurations. Finally, it must be noted that the presented results are interim results within the mentioned research project. Consequently, the results may change over the course of the project, as new information is collected and assumptions may be updated.

5. Conclusion and Outlook

The assessment provides insights into the environmental performance of different heat pump configurations in the context of newly built single-family houses. In this comparison, the GSHP shows the lowest impacts in both the climate change and resource use category. In general, BWHP are smaller than ASHP and therefore need less material. This is due to the smaller heat exchanger on the source side. The ground probe shows lower environmental impacts than the PVT collector. While especially the PV-part of the PVT collector is responsible for environmental impacts, the ground probe consists primarily of a PE pipe. Additionally, the lifetime for the ground probe is 50 years, further reducing the impacts per functional unit. The BWHP+PVT system shows the highest impacts in both investigated categories when no credits are considered. However, this neglects the additional benefit of 2.6 MWh_{el} that leave the system boundaries and are available for use in other applications. To include these additional benefits, environmental credits according to the avoided burden approach have been considered in a sensitivity analysis. The reference for this is PV electricity from a rooftop plant with a carbon footprint of 0.030 kg CO_2-eq./kWh_{el}. This credit lowers the carbon footprint of the heating system to 0.088 kg CO_2-eq./kWh_{th}, which is lower than the carbon footprint of the ASHP system. The same effect can be seen for the category resource use. Without credits, the BWHP+PVT system shows the highest impacts, while the inclusion of credits leads to a reduction of allocated impacts by 31% per FU, which is lower than the resource use impacts of the ASHP+ST system. The comparison of the ASHP and the ASHP+ST system is quite interesting. While the ASHP shows lower impacts in the category resource use, the ASHP+ST system has a lower carbon footprint per FU. While the additional material consumption for the production of the ST collectors is apparent in the resource use category, the benefits of reduced electricity consumption for the heat pump outweigh the additional burden in the category climate change. The ST collectors are capable to provide the hot water demand in the summer months so that the ASHP is not used during that time, reducing the electricity demand of the heating system. The sensitivity analysis shows that this advantage diminishes when the electricity mix is decarbonized. When the projected electricity mix for 2045 is included in the assessment, both systems reach a carbon footprint of 0.026 kg CO_2-eq./kWh_{th}.

In future assessments also single-family houses from the building stock are included as well as multi-family buildings. As mentioned above, the project not only includes heat pump configurations but also other renewable heating systems that will be analyzed in future comparisons. For a comprehensive assessment, the end-of-life phase will be included as well as additional impact categories to identify potential trade-offs.

Data availability statement

The Life Cycle Inventory can be made available upon request.

Author contributions

M. Fischer: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Visualization, Writing – original draft, Writing – review and editing. **S. Herceg**: Methodology, Writing – review and editing. **K.-A. Weiß**: Writing – review & editing, Funding acquisition, Project administration.

Competing interests

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