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Integrated Sustainability Assessment of a Residential Heat Pump System

Approach, Data Requirements, and Integration of a Dynamic Electricity Mix

Marie Fischer[1,*], Sina Herceg[1], and Karl-Anders Weiß[1]

[1] Fraunhofer Institute for Solar Energy Systems ISE, Germany

*Correspondence: Marie Fischer, marie.fischer@ise.fraunhofer.de

Abstract. As there is currently a lack of reliable guidance for investors to make the most sustainable choice when it comes to different renewable heating technologies for residential buildings, this contribution presents a methodological approach for a comprehensive comparison, while also addressing data requirements. A focus point of the methodology development and the sustainability assessment lies on the integration of a dynamic electricity mix to account for the continuous decarbonization in an energy grid that is more and more based on renewables. Its influence on the final environmental impact results of the presented exemplary system combining a solar thermal collector and an air source heat pump is assessed. The results indicate a significant influence of the electricity mix on the carbon footprint (- 48%) of the provided heat. The resource use is only slightly changed (+ 3%).

Keywords: Life Cycle Asessment, Heat Pump, Solar Thermal System, Electricity Mix

1 Introduction

Currently, about 17.4% of the German heat demand are covered through renewable energies (RE) [1]. While biomass is still the largest contributor in the renewable heating market, its share is decreasing. There has been a rapid increase in the utilization of geothermal and ambient heat through the deployment of heat pumps (especially air-source heat pumps) in the past five years [2]. Also, other renewable heating technologies are growing in the market. Currently, roughly 5% of the German heat demand is covered by solar thermal collectors [1].

Renewable energies cover a wide range of technologies. While all technologies cause environmental impacts during their production and end of life phases, the impacts associated to the respective use phases can differ quite significantly. For solar thermal collectors, the use phase is mostly emission-free. The impacts allocated to the use phase of heat pumps are strongly dependent on the electricity mix and the system efficiency. Biomass as a third example causes direct emissions through the burning process. However, emissions from biomass use are considered as biogenic and not fossil emissions. Therefore, currently, biomass is declared to be a carbon neutral energy source. Similarly, costs and potential revenues can differ quite significantly over the lifetime of these systems. Due to this variety in technologies a comprehensive comparison based on both environmental impacts and economic performance is not yet available and investors are lacking reliable guidance for sustainable decisions.

Environmental impacts are quantified and assessed through the life cycle assessment (LCA) methodology. While the general approach is standardized in the ISO standards DIN EN ISO 14040 and 14044 [3, 4], there is still a lot of room for individual choices. This leads to a lack of comparability in the results. Different system boundaries, functional units and impact assessment methodologies make comparisons of LCA results among different studies in many cases impossible. For some technologies, further recommendations and standardizations are available to allow for a fair comparison. However, this is mostly technology specific and does not allow for comparisons of different technologies. In the German Project "Effizientes Heizen" (efficient heating), the project team aims to close this gap by developing a comprehensive approach and guidelines to assess and compare a variety of different heating technologies with regards to their economic and ecological performance. Internationally, this is also supported through the IEA SHC Task 71.

This contribution focuses on the developed methodological guidelines regarding the ecological impacts (LCA), while applying them exemplary to a combined solar thermal and air-source heat pump system. The economic assessment approach is presented in the conference paper by Stephan Fischer, titled "Uniform Modelling of Heat Production Costs in Single-Family and Multi-Family Houses".

2 Methodology

To make LCA results comparable across technologies, key parameters must be defined and standardized. Most importantly, the system boundaries of the LCAs must be harmonized. This includes the decision on which life cycle stages are assessed (raw material extraction, production, use phase, recycling and/or disposal), as well as the definition of the product system: Does the LCA include the entire heating systems setup (e.g., heat generator, heat storage, and distribution) or is the focus solely on a specific component or technology (e.g., heat generator). For a comprehensive, fair, and application-oriented comparison, this project focuses on heating systems over their entire life cycle. To further enhance comparability, the system layout is based on standardized demand side scenarios. Heating systems are designed to meet the demand of predefined reference buildings (single and multi-family houses, newly built and building stock) and are scaled accordingly. As a functional unit, 1 kWh of provided heat (1 kWh_{th}) is used. This refers to the heat provided to the distribution system in the building. It does not include the distribution system itself. These unifications of the functional unit and the system boundaries are essential to make LCA results comparable. The third key factor in standardizing LCA setups is the choice of the life cycle impact assessment method. Following recommendations by the European Commission, the EF3.0 Methodology is selected [5], while relevant impact categories are identified by performing hot spot analyses. The chosen system model is cut-off, while environmental credits, as well as potential loads and benefits beyond the system boundaries may be listed separately, as for example the recyclability of products. Data requirements and quality standards are clearly defined, as well as the procedure on how to fill potential data gaps. Approaches for harmonized data sets for different heating technologies are presented.

While the harmonization of these (rather methodologically focused) aspects allows for limited comparisons of the LCA results, further guidelines and the definition of technological and other input parameters is required. These include, among others, the lifetime of the systems and its components, the efficiency, degradation rates and patterns, the location of installation, the end-of-life treatment of components and the applied electricity mix. As mentioned earlier, impacts allocated to the use phase of heat pumps are strongly dependent on the electricity mix. With increasing RE deployment, the electricity is continuously decarbonized. In a scenario analysis, both the assumption of the current electricity grid mix for the entire use phase of up to 20 years (scenario 1), and a dynamic electricity mix model (scenario 2) are integrated in the modelling of the system. The dynamic electricity mix model allows to account for future grid mix developments. The predictions for the development of the German electricity mix are considered for

20 years (2023 to 2042). The data basis for this is the reference scenario out of a Fraunhofer ISE study from 2021 [6]. This is presented as an example to analyse the influence of the electricity mix on the impact results. The grid mix values for 2023 (in scenario 1) are taken from the grid mix reported in the ISE Energy-Charts [7]. The focus in both scenarios is on the annual average grid mix. Seasonal variations have not been investigated in detail for this contribution. According to preliminary analyses, it can be expected that the change in the grid mix over several years outweighs the intra-yearly differences.

2.1 Goal and Scope

The goal of this life cycle assessment is to quantify the environmental impacts associated to the heat provided by a combined solar thermal and air source heat pump system. A special focus in this analysis lies on the assessment of the influence of a dynamic electricity mix on the overall life cycle impacts. The system boundaries include the production and the use phase, while the end of life is omitted due to a lack of reliable data. However, this data gap is addressed in the project and included at a later stage. The investigated system is scaled according to a pre-defined heating curve of a newly build single family house with an annual heat demand of 9228 kWh including heating and hot water demand. The building is located in Germany. The system includes a solar thermal system of four flat plate collectors as well as an air-source heat pump which feed into the same hot water storage tank. The heating as well as the hot water are provided from this tank. For the domestic hot water supply, a freshwater station is implemented in the system. However due to a lack of reliable LCI data, this particular component is neglected in this LCA. The hot water demand during the summer months is entirely covered by the solar thermal collectors, leading to an overall annual solar fraction of roughly 28.5%. Figure 1 shows a simplified scheme of the investigated system. The air source heat pump (ASHP), the solar collectors and the storage tank, as well as piping and expansion vessels are included in this LCA, while the distribution system lies outside the system boundaries. Further information on the specific components is detailed in the next chapter (Life Cycle Inventory). The system lifetime is assumed to be 20 years, while a 25-year lifetime is tested as a sensitivity analysis. For simplicity, the performance of the heating system is considered to be constant over the investigated lifetime of 20 years, hence, no degradation is included. This refers especially to the electricity consumption and the heat production by the heating system, which are assumed to remain constant.

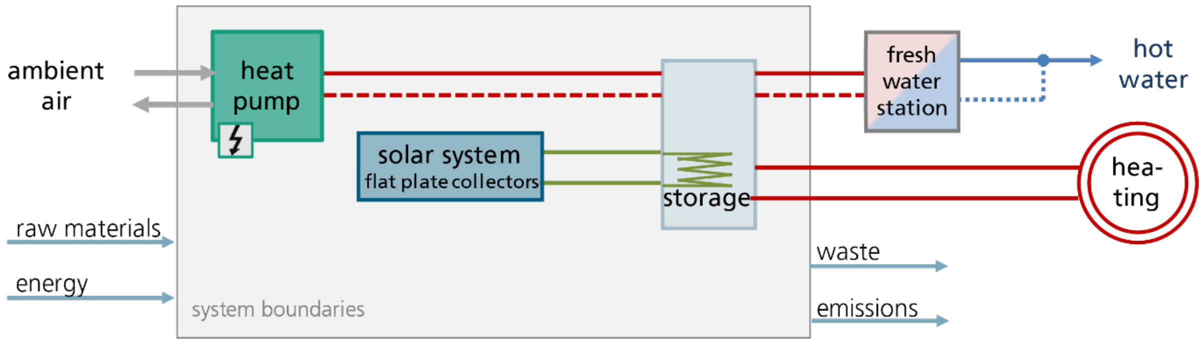

Figure 1: *Schematic system layout and system boundaries of the defined heat pump and solar thermal system including the main components.*

The chosen functional unit is 1 kWh of heat provided to the building to cover the hot water and heating demand. The analysis in conducted using the EF3.0 methodology recommended and provided by the European Commission [5]. In this contribution, the impact categories *climate change*, *ecotoxicity, freshwater* and *resource use, minerals and metals* are investigated in detail. (However, in the project, further impacts are investigated.) The production location for all components is assumed to be Europe. Transport distances to the installation site are not included in this analysis.

2.2 Life Cycle Inventory

The heating system is modelled in the LCA software SimaPro (v9.5.0.2) with ecoinvent (v3.8) as the background database. The foreground data is sourced from project and literature data. The scaling of the system and its components (type/size/nominal power of heat pump/collectors/tank), as well as performance parameters (electricity demand in the use phase, solar fraction) are taken from project data and matches the energy requirements of the defined reference building. (The LCI data is given in the Annex.)

The air source heat pump has a nominal power of 2.5 kW at A2/W35. It weighs 150 kg and 2.18 kg of refrigerant (R410a) is used. In line with [8], a 2% loss of refrigerant is assumed upon installation. The LCI has been derived from an average based on [9–12] and is included in Table 2 in the Annex. Additionally to the ASHP, the system includes four solar thermal collectors covering about 2.5 m² each. The LCI data for the solar collector is derived from project data, including adjustments based on ecoinvent information [13]. The heat carrier in the system is a water and propylene glycol mixture. Based on literature and manufacturer information, it is assumed, that the solar fluid must be replaced after ten years. The solar thermal system includes a 25-l expansion vessel as well as insulated copper piping. The heating system is completed by a hot water tank with a volume of 750 l and a 100-l expansion vessel. The LCI for the hot water tank is taken from [14] and scaled down to the required size, while the expansion vessel is taken from ecoinvent [13]. The electricity mix data for the year 2023 is taken from [7]. The predictions on the development of the German grid mix over the next 20 years is taken from the reference scenario in [6].

For the use phase, the electricity consumption is calculated through system simulations using PolySun. For this heating system an annual electricity demand of 2825 kWh_{el} is calculated, with a thermal energy production of 9261 kWh_{th}.

3 Life Cycle Impact Assessment and Interpretation

The EF3.0 methodology is applied for the impact assessment. As mentioned, the focus in this paper is on the impact categories *climate change*, *ecotoxicity, freshwater* and *resource use, minerals and metals*. In the following, the impact assessment results are presented in detail.

3.1 Production Phase

First, the production of the system is analyzed. An overview on the contributions of the system components on the overall production impacts in the three investigated categories is shown in Figure 2. The ASHP contributes 65% of the carbon footprint of the production phase. The production of the solar thermal system causes 23% of the *climate change* impacts, while the share of the hot water tank lies at 11%. The expansion vessel contributes about 1% to the environmental impacts in this category. For *ecotoxicity*, the shares are somewhat comparable. However, the solar thermal system contributes around one third of the production impacts, while the production of the hot water tank is only responsible for less than 3% of the impacts. The impacts attributable to the expansion vessel make up 0.3%. When looking at the impact category *resource use, minerals and metals*, the impacts caused by the hot water tank and the expansion vessel are negligibly low. About 71% of the impacts in this category are due to the ASHP production, while 28% are attributable to the production phase of the solar system.

Within the ASHP, the main sources of impacts are the use of copper and the electronic control unit. For *ecotoxicity* and *resource use*, they are responsible for about 95% of the production impacts. For *climate change*, also the electricity and heat consumption in the production process are a considerable source of impacts, with a combined contribution of almost 16% to the carbon footprint. Other materials such as steel, insulation and aluminum make up the remaining 14% of the *climate change* impacts. The refrigerant (R410a) contributes less than 1% in all three categories.

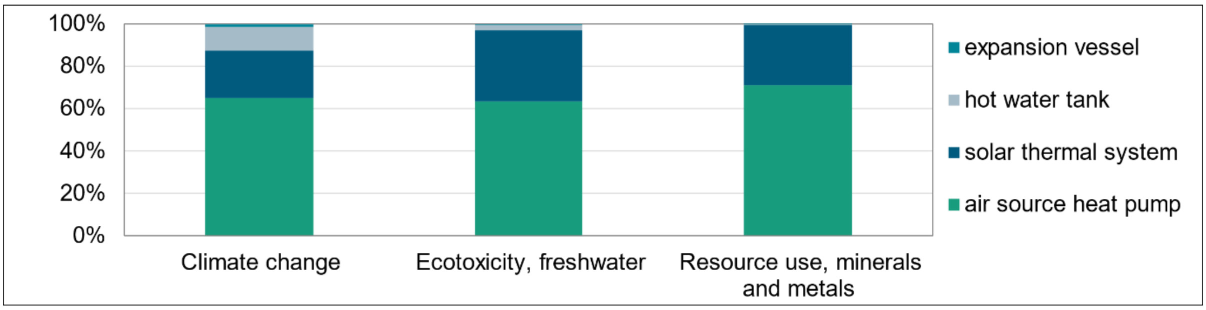

Figure 2: *Contributions of the different investigated components to the overall impacts of the defined heating system per impact category. The functional unit is the heating system itself. Impact Assessment Method: EF3.0, Characterization.*

Besides the actual collectors, the solar thermal system also includes insulated copper piping, the solar fluid and a 25-l expansion vessel. While the collectors cause the majority of the environmental impacts in all three categories within the solar system, especially in the *ecotoxicity* and the *resource use* categories, also the copper pipes show a significant impact with 38% and 44%, respectively. The piping and the solar fluid contribute 10% and 8% to the carbon footprint of the solar thermal system, respectively, while the contribution by the solar thermal collectors is at 78%. The main contributors to the *climate change* impacts in the collectors are aluminum and plastics usage, the copper and the solar glass.

The hot water tank is made from steel, which causes more than 85% of its production impacts in all three investigated categories. It is insulated with glass wool, which contributes between 4% and 7% depending on the impact category. The heat and electricity consumption in the production contribute around 7% of the impacts in the *climate change* category.

3.2 Use Phase

In order to make a more comprehensive assessment, also the use phase must be addressed. The use phase includes the electricity demand as well as the replacement of the solar fluid after ten years. As there is no consent regarding a potential leakage of refrigerant in the heat pump LCA literature, this is not included. However, it is assessed separately in a sensitivity analysis. Two scenarios are investigated regarding the electricity mix used during operation. First, the environmental impacts associated to the usage of a constant electricity mix over the entire 20-year system lifetime are quantified and assessed in scenario 1. Secondly, the predicted development of the German grid mix is considered, accounting for annual changes in the average German electricity mix in scenario 2.

3.2.1 Scenario 1: Constant electricity grid mix

For the constant electricity mix, the reported 2023 average German grid mix is sourced from the ISE Energy Charts [7]. 41% of the electricity originated from renewable sources, while 59% of the grid mix is sourced from fossil fuels. The largest share of electricity was provided by onshore wind turbines with more than 26% in 2023. The calculated carbon footprint of that year's electricity mix is 0.433 kg CO_2 eq/kWh_{el}.

Considering this as the constant electricity mix over the entire system lifetime of 20 years, the carbon footprint of the heat provided by the heating system is 0.152 kg CO_2 eq/kWh_{th}. As shown in Figure 3, the electricity consumption dominates the *climate change* impacts with a contribution of nearly 90%. The contribution of the use phase in the other two investigated categories is significantly lower with 29% and 5% for *ecotoxicity* and *resource use*, respectively. The refilling of the solar fluid (propylene glycol) has no visible impacts in any of the investigated categories.

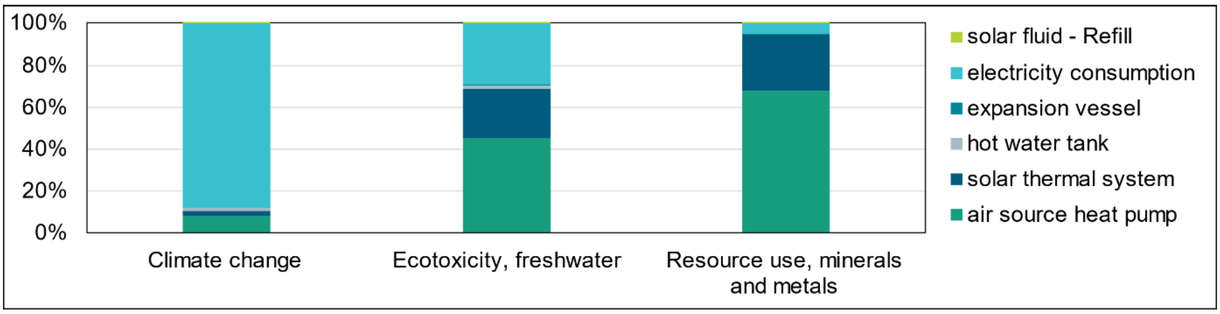

Figure 3: *Contributions to the Life Cycle Impacts of the defined heating system with a constant electricity mix (Scenario 1) by impact category. The production and use phase impacts are shown. The functional unit is 1 kWh$_{th}$ provided by the heating system. Impact Assessment Method: EF3.0, Characterization.*

3.2.2 Scenario 2: Influence of dynamic electricity mix

As the decarbonization of the electricity mix is progressing, using a constant electricity mix for a period of 20 years may lead to an overestimation of the carbon footprint attributable to the heat provided by the defined heating system. Therefore, also a dynamic electricity mix was implemented to reflect the predicted developments over the next two decades. These predictions were taken from the reference scenario in [6] and implemented in SimaPro. While they present the time horizon until 2045 in their study, only 20 years are considered for this assessment (2023 to 2042). The predicted grid mix in 2042 contains nearly 90% of solar and wind powered electricity, and roughly 6% of the electricity mix is provided by gas-fired power plants. This is reflected in the carbon footprint of this grid mix of 0.101 kg CO_2 eq/kWh$_{el}$.

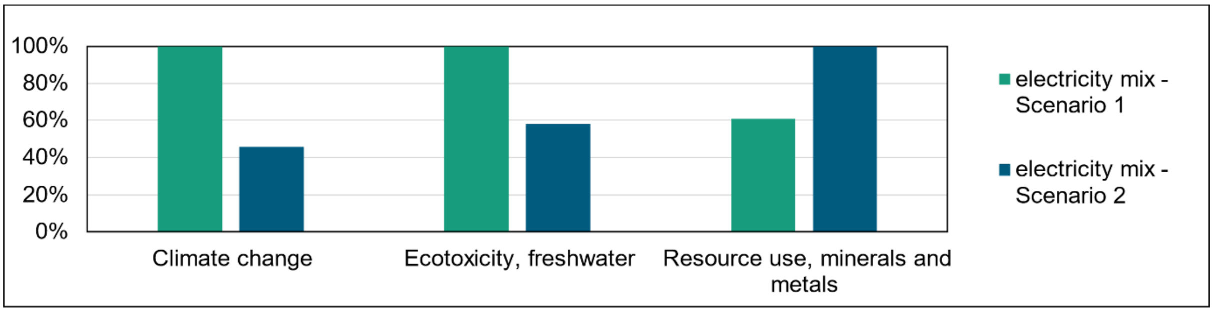

Figure 4: *Comparison of the environmental footprint of the electricity mixes in Scenario 1 and 2. The larger impact value per category is defined as 100%, while the other is depicted relative to this. The functional unit is 1 kWh$_{el}$. Impact Assessment Method: EF3.0, Characterization.*

To account for these projected emission reductions, a dynamic electricity grid mix modelling was implemented. Scenario 2, therefore, reflects not only the grid mix in 2023 and 2042, but also the development of the annual averages. This dynamic grid mix leads to an average carbon footprint of 0.198 kg CO_2 eq/kWh$_{el}$. This constitutes a 54% reduction in *climate change* impacts per kWh$_{el}$, compared to the 2023 grid mix. The development in the *ecotoxicity* category is similar. Here, a reduction by 42% of the impacts when comparing the dynamic grid mix with the 2023 data is achieved. However, the trend in the *resource use* category is contrary. Here, the impacts increase with increasing renewable energies in the mix. This is because renewable energy technologies have a much higher resource consumption in the production phase due to their complexity, while using little to no fuel in the use phase. (Fossil fuel usage is accounted for in a different category, as this resource use category refers specifically to minerals and metals.) The *resource use* impacts of the dynamic grid mix (scenario 2) are 63% higher than the 2023 baseline (scenario 1).

When this dynamic electricity model is implemented into the heating system, its influence on the impacts relative to the chosen functional unit of 1 kWh_{th} can be quantified. An overview is depicted in Figure 5. The reduction of the carbon footprint of the heat provided by the ASHP and solar thermal system is significant. As mentioned above, the carbon footprint calculated on the basis of the static electricity mix (scenario 1) is at 0.152 kg CO_2 eq/kWh_{th}. When the development and decarbonization of the electricity mix is considered (scenario 2), the carbon footprint attributed to the heating system is calculated at 0.080 kg CO_2 eq/kWh_{th}. This is a reduction of 48%. The *ecotoxicity* impacts are also reduced, even if not as significantly as the greenhouse gas emissions. Here, the consideration of the grid mix development leads to a 12% lower impact value per kWh_{th}. Finally, the impacts in the category *resource use, minerals and metals* are increased by 3% compared to the 2023 baseline. Since the impact of the use phase is comparably low in the category resource use, the change in the electricity mix has less influence in this category.

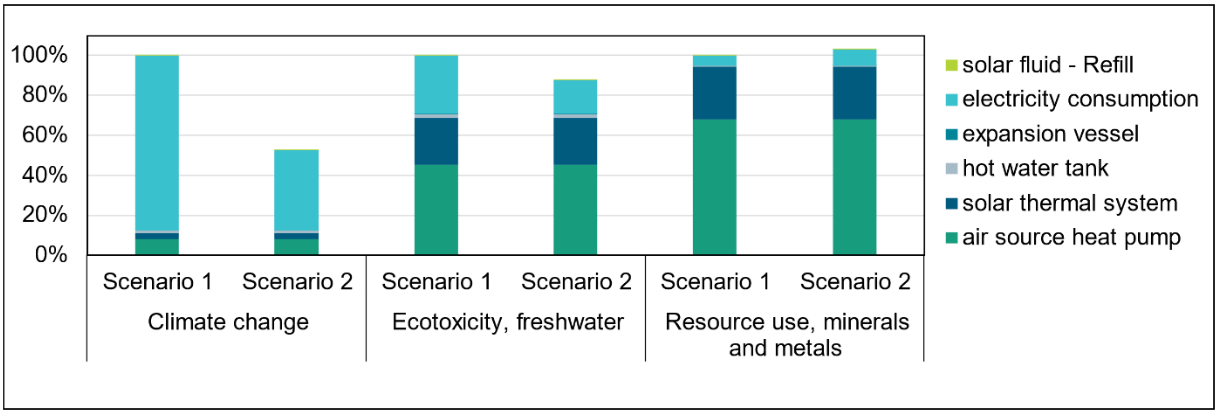

Figure 5: *Comparison of ad contributions to the life cycle emissions in both scenarios by impact category. The production and use phase impacts are shown. The impacts of scenario 1 are defined as 100% in each impact category, while the impacts of scenario 2 are displayed relative to this. The functional unit is 1 kWh_{th} provided by the heating system. Impact Assessment Method: EF3.0, Characterization.*

3.3 Sensitivity analyses

The conducted sensitivity analyses are done using the assumptions of scenario 2, which is therefore also the baseline for comparisons.

3.3.1 Refrigerant Leakage

As mentioned above, the leakage of refrigerant from the heat pump is evaluated through a sensitivity analysis. In the literature, different leakage rates have been considered by different authors. [8, 11] consider annual leakage rates of 2% to 3.5%, while [9, 15] set this value at 6%. In this article, this higher value of 6% for the annual leakage rate has been chosen to test the sensitivity. Although, this can be considered a conservatively high value, the results show negligibly low changes in all three categories (< 0.1%) per functional unit.

3.3.2 25-year Lifetime

In most LCA studies, the lifetime of heat pump system is assumed to be 20 years. However, following [12], also a 25-year lifetime may be realistic. Therefore, this was also tested as a sensitivity analysis with a dynamic electricity mix for the next 25 years. The results show a 17% to 18% impact reduction per kWh_{th} for all three categories when compared to scenario 2.

4 Discussion

The results show a significant influence of the electricity mix on the environmental footprint of the presented heating system. The *climate change* impacts are largely dependent on the electricity source that is used in the assessment. The constant decarbonization of the grid mix therefore shows significant impacts in the system's life cycle impacts. This is due to the reduction of the share of fossil-based electricity from 41% in 2023 to an average of 20% in the dynamic electricity mix model. Consequently, the share of renewables has been increased from 59% to 80% from scenario 1 to scenario 2. The reduction in *ecotoxicity* impacts is largely caused by the reduction of the share of coal-based electricity in the grid mix. The reduction by 42% in the electricity mix impacts from scenario 1 to scenario 2, results in a decrease of 12% when looking at the *ecotoxicity* impacts of the heating system per kWh_{th}. Only in the *resource use, minerals and metals* category, the impacts allocated to the electricity mix are significantly increased by the deployment of renewable electricity sources. The impacts per kWh_{el} are increased by 64% from scenario 1 to scenario 2. Since the influence of the use phase in this category, however, is comparably low, the overall changes of the impacts per kWh_{th} are at only 3%. Still, these results further highlight the importance of a broad ecological assessment, to identify trade-offs. Even though the carbon footprint can be significantly reduced, there are increases in other impact categories. In order to make sustainable choices, a comprehensive assessment is required.

The presented results are comparable to previous studies. Greening et al. [9] found in their comparative LCA study of different heat pumps and a gas boiler, a carbon footprint of 0.276 kg CO_2 eq/kWh_{th}. The study was published in 2010, which explains the low share of renewables in their applied electricity mix of 5%. Further, they included transport impacts, which are not considered in this paper. The authors investigated different RE penetration scenarios for the grid and its influence on the heat pump's environmental footprint. They found a 50% emission reduction potential when the RE share in the grid mix is increased from 5% to 80% [9].

A more recent study found a carbon footprint of 0.109 kg CO_2 eq/kWh_{th} for the production, installation and use phase [12]. The applied electricity mix was the Italian grid mix. The system lifetime was assumed to be 25 years. This is in line with the results presented in this study, as scenario 1 shows higher impacts per kWh_{th}, as it only considers a system lifetime of 20 years. The sensitivity analysis including the dynamic electricity mix for a lifetime of 25 years, shows a significantly lower impact value of 0.066 kg CO_2 eq/kWh_{th}.

Finally, Kägi et al. [11] published LCI data on different heat pumps and other components in 2021. They calculated a carbon footprint for the production of a 7 kW (256 kg) ASHP at 3060 kg CO_2 eq. Since the operation that the 7 kW of rated power refers to is not specified, the weight of the heat pump is used for comparison. In relation to the weight, the impacts of the heat pump production in this paper are slightly higher than the ones calculated by Kägi et al. This deviation may be due to scaling effects or underlying energy mixes.

Overall, the presented results are in an expectable range when compared to other LCA studies. Still, it must be pointed out, that there are certain limitations to the presented results. First and foremost, the future electricity development is unknown, and therefore the predictions entail high levels of uncertainty. Still, it was shown that it is very important to take these predictions into consideration. The prediction for the grid mix was done by economic optimization principles and does not necessarily reflect the actual development in the next decades [6]. In the study, several grid mix development scenarios were presented, however, only the reference scenario was implemented in this research. A broader understanding of the influence of the electricity mix on the environmental footprint of the operation of the presented heating system may be reached by including additional scenarios.

For simplicity, no degradation of the system was considered. Also, a constant annual electricity demand and heat production were assumed. However, depending on weather conditions and mid-term climate developments, both values will vary among the different years. A more in-depths analysis including historical monitoring data of heating systems in combination with weather data could deliver valuable insights in this regard.

Finally, the end of life of the system as well as transportation efforts are not included in this study. This may lead to an underestimation of the overall impact results and will be addressed at a later stage within the research project.

The impacts in the category *resource consumption, minerals and metals* are the only ones in this analysis, that are increased due to the integration of the dynamic electricity model. Renewable energies require more materials and rare earths in their production than fossil energy systems. This development highlights the need for a consistent transformation of linear supply chains towards a circular economy. The transformation to a circular economy will not only lower the impacts of the electricity mix, but also the ones allocated to the production phase of the heating system itself. The circulation of resources will play a major role in the near future. It is an essential part in order to minimize environmental impacts, while ensuring the security of supply of various key materials in the long-term.

5 Conclusion and Outlook

Overall, it can be concluded that the electricity mix has a significant influence on the ecological performance of a combined solar thermal and air source heat pump system. While the impacts in the categories *climate change* and *ecotoxicity* are decreased with a higher share in renewable energies, the *resource use* impacts are slightly higher than the baseline. When a constant electricity grid mix is assumed to calculate the environmental impacts of a heat pump and solar thermal system, the results are – depending on the category – an over- or underestimation of the actual impacts. Especially when these results are compared to other technologies that use little or no electricity in the use phase, this is an important aspect to consider, as it may lead to an unfair comparison.

The results highlight the importance of the decarbonization of the electricity grid mix, especially regarding the projected heat pump deployment. At the same time, the transformation towards a circular economy is a key issue that needs to be addressed as resource consumption is a critical issue. The results indicate that with linear supply chains, the *resource use* impacts will continue to increase with the deployment of renewable energies. For a sustainable transformation, the material loop must be closed.

While in this assessment, the focus was on one specific scenario regarding the grid mix development, future studies should assess a variety of possible grid mix developments to test sensitivities in that regard and to identify potential trade-offs between different development scenarios.

Data availability statement

The life cycle inventory (LCI) data is included in the Annex of this paper. This specifically refers to the heat pump and the electricity mixes. The LCI of the solar collector cannot be disclosed at this time, as this includes confidential project data. LCI data that is taken from literature is cited accordingly.

Author contributions

Marie Fischer: Conceptualization, Methodology, Data curation, Formal Analysis, Investigation, Validation, Visualization, Writing – original draft, Writing – review & editing. Sina Herceg: Conceptualization, Funding acquisition, Writing – review & editing, Supervision. Karl-Anders Weiß: Project administration, Funding acquisition, Writing – review & editing, Supervision.

Competing interests

The authors declare that they have no competing interests.

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Annex: Life Cycle Inventory

Table 1: *Life Cycle Inventory: Production phase of the presented heating system. The LCI for the air source heat pump is given in Table 2, while the data for the solar thermal system is detailed in Table 3. The LCI for the hot water tank is taken from [14] and scaled to 750 l. The expansion vessel-data is taken from [13] and scaled to 100 l.*

Output		
Combined Air Source Heat Pump and Solar Thermal Heating System	1	p
Inputs		
Air source heat pump [2,5 kW at A2/W35]	1.00E+00	p
Solar thermal system	1.00E+00	p
Hot water tank	7.50E+02	l
Expansion vessel, 80l	1.25E+00	p

Table 2: *Life Cycle Inventory: Production of an air source heat pump. The Inventory is calculated as an average data set from [9–12]. The background data is taken from [13].*

Output		
Air source heat pump [2,5 kW at A2/W35]	1	p
Inputs		
Aluminium alloy, AlMg3	7.22E+00	kg
Brass	1.05E-02	kg
Copper	2.86E+01	kg
Electricity, medium voltage	1.88E+02	kWh
Electronic component	1.14E+00	kg
Heat (biomethane)	4.92E+02	kWh
Heat (natural gas)	8.19E+02	kWh
Heat (light fuel oil)	3.30E+01	kWh
Heat (softwood chips)	3.99E+02	kWh
Lubricating oil	1.39E+00	kg
Polyethylene, linear low density, granulate	1.52E-01	kg
Polyvinylchloride, bulk polymerised	9.50E-01	kg
Reinforcing steel	4.96E+01	kg
Steel, low-alloyed, hot rolled	4.77E+01	kg
Stone wool	9.88E-01	kg
Tap water	6.63E-01	kg
Tube insulation, elastomere	9.51E+00	kg

Table 3: *Life Cycle Inventory: Production of the solar thermal system. The system includes collectors, piping, and an expansion vessel. Amounts are based on project data.*

Outputs		
Solar thermal system	1	p
Inputs		
Solar thermal collectors	4.00E+00	p
Propylene Glycol	3.39E+01	kg
Copper (pipes)	1.17E+01	kg
Tube insulation, elastomere	6.75E-01	kg
Expansion vessel, 25l	1.00E+00	p

Table 4: *Relative shares of energy sources in the applied electricity mixes in the use-phase of the heating system. Data for Scenario 1 is taken from [7]. The average electricity mixes for Scenario 2 and the sensitivity analysis are calculated based on [6].*

	Scenario 1	**Scenario 2**	**Sensitivity Analysis: 25-year lifetime**
Brown coal	17.9%	2.8%	2.0%
Hard coal	8.0%	1.5%	1.1%
Natural gas	10.3%	14.6%	12.4%
Nuclear Energy	1.6%	0.0%	0.0%
Oil	0.7%	0.0%	0.0%
Biomass	9.6%	0.4%	0.3%
Hydropower	4.5%	1.9%	1.7%
Hydrogen	0.0%	0.2%	0.6%
Solar	12.3%	27.8%	28.9%
Wind Onshore	26.8%	25.5%	26.7%
Wind Offshore	5.4%	23.8%	24.9%
Others	2.9%	1.5%	1.5%