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Comparative Analysis of Resource and Climate Footprints for Different Heating Systems in Building Information Modeling

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Abstract: Buildings play an important role to meet Sustainable Development Goals, especially regarding the use of resources and greenhouse gas emissions. They are increasingly designed with energy-efficient solutions regarding their operations, while the related use of natural resources is still insufficiently considered. In this article, a methodology in Building Information Modeling is proposed to measure the resource and climate footprints of buildings' heating systems. The methodology is applied to a case study building in Germany. The studied heating systems include a gas condensing boiler, ground-source heat pump, ground-source heat pump with a photo-voltaic system and air-source heat pump backed up with a gas boiler. Next to the operational energy, the production and transport of the heating systems were also studied. Results show that heating system operations have the largest impact and that the variant of ground-source heat pump combined with photovoltaics (GSHP + PV) has the lowest impact. In comparison with the gas boiler (GB), savings of 75%, 47%, 80%, and 84% are addressed to climate, material, energy, and land footprints, respectively, while the water footprint of GSHP + PV is 73% higher than that of GB.

Keywords: life cycle assessment; building information modeling; design phase; resource efficiency; energy efficiency

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1. Introduction

Economic developments in the building sector have caused a significant increase in environmental pressures. Those pressures include not only a boost in greenhouse gas (GHG) emissions but also excessive use of resources [1–3]. These pressures caused by the building sector led to significant environmental impacts in different categories such as global warming, water scarcity, land use change, and biodiversity loss [4,5].

Globally, buildings represent 36% of the total energy consumption, and 53% of the building energy consumption is driven by space and water heating [6]. In Germany in 2019, more than 70% of the energy used for space heating in residential buildings was generated from gas and oil [7]. To reduce environmental impacts, a shift towards renewable heating systems is required. There are already various low-emission heating solutions available, such as biomass boilers or heat pumps that run on renewable electricity. Even though these alternatives allow for significant reductions in GHG emissions, their environmental impacts in terms of material, water, and land use should not be disregarded. Methodologies are required to enable building planners to facilitate the consideration of these aspects in the early design phases of buildings.

Building Information Modelling (BIM) allows architects and engineers to design detailed 3D models of buildings and to communicate efficiently via dedicated Computer-Assisted Design (CAD) software. Combining BIM with both energy analysis and environmental impact assessment could facilitate the choice of a low-impact heating system and improve the building's environmental performance [8].

The environmental impacts of buildings can be evaluated using Life Cycle Assessment (LCA) according to ISO 14040 [9] and ISO 14044 [10]. LCA enables the quantification of environmental impacts from GHG emissions such as global warming, as well as from the use of material resources, energy, water, and land of a product or service over the whole life cycle [11]. EN 15804 describes the LCA boundaries for specific construction materials or a product, whereas EN 15978 regulates the assessment of the environmental performance of buildings [12,13].

Many studies have conducted LCA of buildings [14–18]. Famiglietti et al., (2022) [19] developed a tool that enhances the LCA of the building during the operational phase. The tool was tested with about 81,000 buildings in Milan city and 161,935 energy systems were investigated. The results showed that space heating is the main contributor to global warming at about 77%, followed by domestic hot water at 12%, and space cooling at 11%. The tool permits the LCA of the building sector in large-scale cities considering different environmental impact categories. Haddad et al. (2022) [20] proposed an environmental management tool for the selection of hot water systems for buildings considering BIM and LCA. The approach was tested by conducting a comparative analysis of solar-heating water systems and natural gas-heating water systems for a residential building in Brazil. The results showed that the climate footprint of the natural gas system is higher than that of the solar heating system, whereas most of the freshwater consumption is accounted for by the solar heating system. Tushar et al. (2021) [21] developed a BIM-based framework to combine an energy-rating tool with LCA to enhance the decision-making regarding the passive design of buildings. Consequently, the energy consumption and LCA results were varied for different design factors, e.g., shading, insulation, orientation, and window glazing. Najjar et al. (2019) [22] developed an LCA methodology integrated with BIM that focuses on the decision-making process and sustainability perspectives. The study results indicated that considering steel construction instead of concrete could have better environmental performance and reduce energy consumption during the operation of the building. Rezaei et al., (2019) [23] used Revit for BIM and the software openLCA with the database ecoinvent to conduct an LCA of a residential building in Canada. The environmental impacts were optimized according to different building designs in the early and detailed planning phases. Panteli et al. (2018) [24] developed a model for the optimal computational design of building overhangs in terms of LCA within BIM. Different alternatives of shading, orientations, and climatic data had been studied to develop benchmark values for constructing bioclimatic elements. Gamarra et al. (2020) [25] analyzed the direct input of the energy, material, and water of two schools located in a hot climate area and assessed the direct energy and water consumption and the GHG emissions per student. Different improvement scenarios have been studied such as the use of renewable energies or the use of different alternatives to increase energy efficiency. As a result, the demand for fossil energy can be reduced regarding their operation phase by the consideration of renewable heating solutions and lighting substitution measures. Emami et al. (2019) [26] estimated the environmental impacts of two residential buildings using the LCA databases ecoinvent and GaBi to recognize the uniformity and inconsistencies. Heating systems were assessed under the systems category of the building elements and materials. Fifteen environmental impact categories were considered in the assessment; however, the material footprint was not in the scope of the study. Ingrao et al. (2018) [27] investigated LCA to enhance the design of buildings in terms of energy efficiency and environmental performance. The article highlighted the necessity of LCA applications in buildings to increase resource efficiency and make improvements regarding energy consumption and environmental performance of the whole building. Slorach et al. (2021) [28] assessed the environmental sustainability of different heating technologies in the UK, which are natural gas boilers, air source heat pumps, hydrogen boilers, and direct electric heaters. The environmental impact categories from ReCiPe 2016 were considered [29]. One kWh of heat was deemed as the functional unit. The results concluded that gas boilers have GHG emissions of 220 g CO_2 eq./kWh, which could be decreased to 64 g CO_2 eq./kWh in the case of hydrogen boilers, as the fuels for the hydrogen boilers are natural gas incorporated with carbon capture. Gas boilers have a better environmental performance regarding toxicities and eutrophication, however high GHG emissions were addressed.

The literature review shows that the focus of previous studies was mostly on the environmental impacts of the operational energy of the building, whereas the impacts related to the production of the heating systems were less studied. Moreover, most of the studies have not considered the use of material and water resources. The goal of this article is to propose a methodology for building planners to calculate the resource and climate footprints of different heating systems to facilitate the choice in an early design phase. Resource footprints are assessing the environmental impacts related to material, water, and land use, while climate footprint is assessing the contribution to global warming.

2. Materials and Methods

This section describes the main methods to conduct the LCA study. An overview of the system boundaries is given. Environmental impact categories are described in addition to the information related to the BIM model of the case study. Specifications of the energy analysis and the scope of the LCA are also addressed.

2.1. System Description

The research methodology of the article is shown in Figure 1.

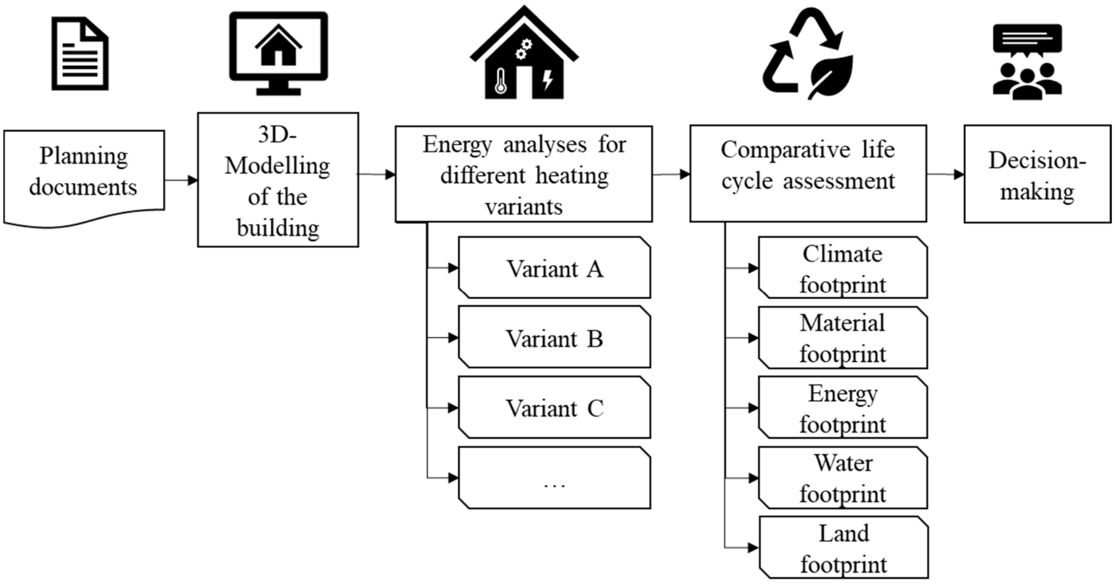

Figure 1. Research methodology.

The workflow includes the planning concept of the building and defines the main parameters that influence the energy analysis and selection of the heating systems of the building such as the building envelope and its usage type. The calculation of the final energy demand is done within the BIM modeling depending on many factors e. g. climate zone, building insulation and orientation, and which type of heating system is needed. The quantification of resource and climate footprints can be achieved according to the results of the energy analysis and information available from the LCA databases ecoinvent and GaBi. Final energy requirements are calculated using different heating systems.

Regarding the German context, the energy analysis is based on the norm DIN 18599-10 [30]. The LCA of the heating systems is based on DIN EN 15804 [31] and the building operational energy is quantified according to DIN EN15978 [32].

2.2. Functional Unit

A functional unit (FU) enables the comparison of different products that are supposed to provide the same functionality and service. In this article, the FU is the provision of the final energy for the whole building in MWh per year with the following specifications:

> "Providing the building with space heating, in a way that maintains the indoor temperature of heated zones at 17 °C for circulation areas, storage areas, and technical rooms, and at 21 °C for offices, meeting rooms, and sanitary rooms, as required by the German building regulation and as specified in DIN 18599-10, for a fixed insulation standard".

2.3. Description of the Resource and Climate Footprint Indicators

Two indicators are used to determine the material footprint: The Raw Material Input (RMI) and the Total Material Requirement (TMR) [33]. Both indicators are referring to the environmental impacts of material resource use within the LCA boundaries. The RMI measures the cumulative used raw materials. The extraction process of raw materials is always associated with unused extraction. The unused extraction is the part of the primary material that is moved and dumped but not further processed and has no economic value, e.g., the overburden of a mine. The TMR measures the total extraction of primary materials from and within nature, as the sum of used and unused extraction. The RMI and TMR can be considered adequate indicators to assess the material footprint of building materials [34,35]. Only abiotic material resources are considered within the scope of this assessment.

The energy footprint is determined by the Cumulative Energy Demand (CED). The CED accounts for the life cycle-wide direct and indirect primary energy consumption, including energy consumption for the extraction, production, and disposal of raw materials [36]. The CED considers renewable and non-renewable energy resources.

The principles for determining and reporting the water footprint are defined in ISO 14046 (2014) [37]. Within the conventional Life Cycle Impact Assessment (LCIA) methods, there are several indicators with different calculation models, considering water use. The AWARE (Available Water Remaining) method was developed to determine the amount of the remaining water in a catchment area or a country, after the water demand of humans, animals, and plants has been met [38,39]. Hence, AWARE addresses the potential vulnerability of a catchment area to water stress. For the calculation of the characterization factors, the AMD (Availability Minus Demand) is used, which is made up of the water availability minus the human and environmental requirements in relation to the reference area.

The land footprint is assessed according to ReCiPe [29]. It is described as land transformation, occupation, and relaxation. Transformation can degrade land quality, defined as the capacity of the soil to provide life support functions. The land is used during the occupation phase, and land quality usually stagnates or decreases. When the occupation is over, the land relaxes and returns to a (semi-)natural state. In the ReCiPe framework, the result is expressed in annual crop equivalent per year, which refers to the relative species loss related to the one-year occupation of land. While the ReCiPe method has been used to assess the land footprint, other methods may also be considered to operationalize the land footprint within the BIM method developed.

The product climate footprint is calculated based on the Global Warming Impact (GWI) per FU expressed in kg CO_2 equivalents. The characterization model with a time horizon of 100 years is used [40], based on the GWP_{100} values of the International Panel of Climate Change (IPCC) [41].

3. Applying the Methodology

3.1. BIM Model of the Case Study

The proposed methodology was applied to the design of new buildings in the city of Korbach, Germany (town hall office building). It includes a renovated historical building with a 676 m^2 building area, an adjacent newly built building, the main building with three floors and a 3727 m^2 building area, and a secondary building with a 1711 m^2 building area, which has also three floors (Figure 2).

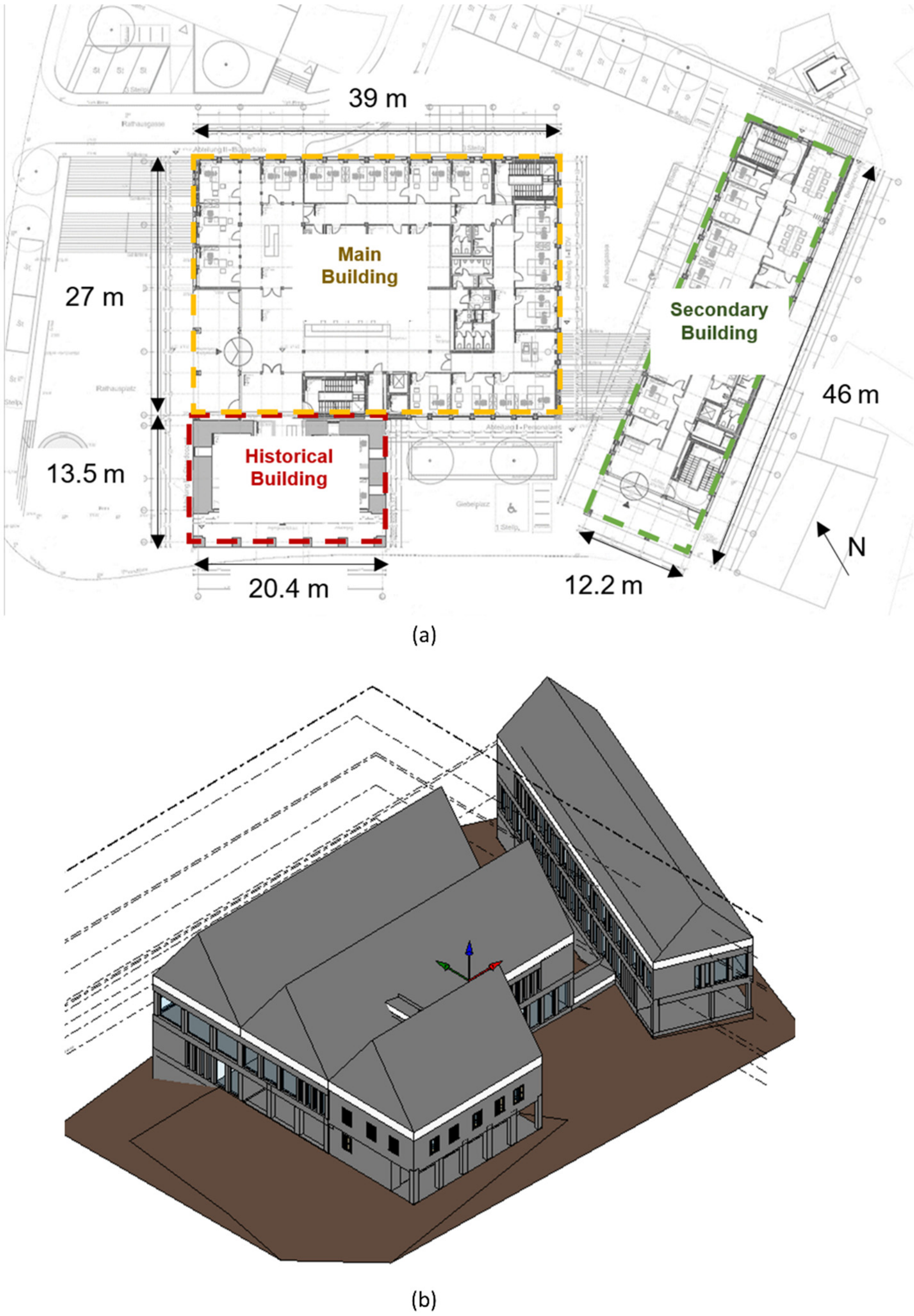

Figure 2. (**a**) Floor plans of the case study building after [42], (**b**) Buildings model.

The first floor of the main building has a 209 m^2 parking lot. Technical areas and ancillary spaces are located partly on the first floor and under the roof. The buildings were modeled using the BIM software Autodesk Revit [43], based on the planning documents provided by the architects. The thermal transmittance values (U-values) of the building elements are described in Table 1.

Table 1. U-values of the building elements.

Building Component	Thermal Transmittance (U-Value) [W/(m^2·K)]
Foundation	0.154
Underground exterior walls	0.195
Exterior walls	0.167
Exterior walls historical	0.450
Upper ceilings	0.140
Roofs	0.086
Windows	1.200
Glass facade	1.100
Doors	1.300

3.2. Energy Modeling

The model of the three buildings was exported from the modeling software (Revit Autodesk) to the energy analysis software, SOLAR-Computer [44] as a gbxml-file. The gbxml-file describes the buildings' geometry, geographical location, and thermal properties. The calculation of the building's energy requirements was done according to DIN EN 18599-10 [45]. Zoning of the conditioned spaces was done in Revit and then transferred to the Solarcomputer software. It consisted of assigning to each space of the building a conditioning profile (including a setpoint heating temperature). By means of these conditioning profiles, several assumptions were made. It was assumed that the town hall is occupied daily from 7 am to 6 pm, five days a week. The setpoint heating temperature was set to 21 °C in the office, meeting, and sanitary rooms. Circulation areas, storage areas, and ancillary spaces are heated at 17 °C. It was assumed that minimum summer heat protection requirements are satisfied. A centralized ventilation system with heat recovery provides fresh air in the building. Concerning space heating, four central heating systems were compared:

- Gas boiler (GB)
- Ground-source heat pump (GSHP)
- Ground-source heat pump with a photovoltaic system (GSHP + PV)
- Air-source heat pump backed up with a gas boiler (ASHP + GB)

The gas boiler (GB) variant represents the conventional way to provide space heating with natural gas and serves as a baseline for the comparison analysis. Current trends focusing on reducing GHG emissions support the development of more efficient technologies running on renewable energy sources. Several scenarios for sustainable developments depict renewably powered heat pumps as one of the best ways to provide space heating and warm water in buildings [46,47]. Heat sources can be ground (Ground-Source Heat Pump, GSHP), air (Air-Source Heat Pump, ASHP), or water (Water-Source Heat Pump, WSHP).

As the environmental impacts of the heat pump variants are largely determined by the electricity mix, it was chosen to compare the impact of a GSHP powered by the German grid mix with a heat pump partially powered by a rooftop PV system (GSHP + PV). The PV system produces about 168 MWh/a, but only 14 MWh/a are consumed directly by the heat pump and therefore considered in the calculation. The ASHP is easier to implement than a GSHP and has a significant market share. It was considered in the form of a hybrid system with a gas boiler as backup (ASHP + GB). Figure 3 presents the buildings' energy concept for the four heating systems, with the system size and power.

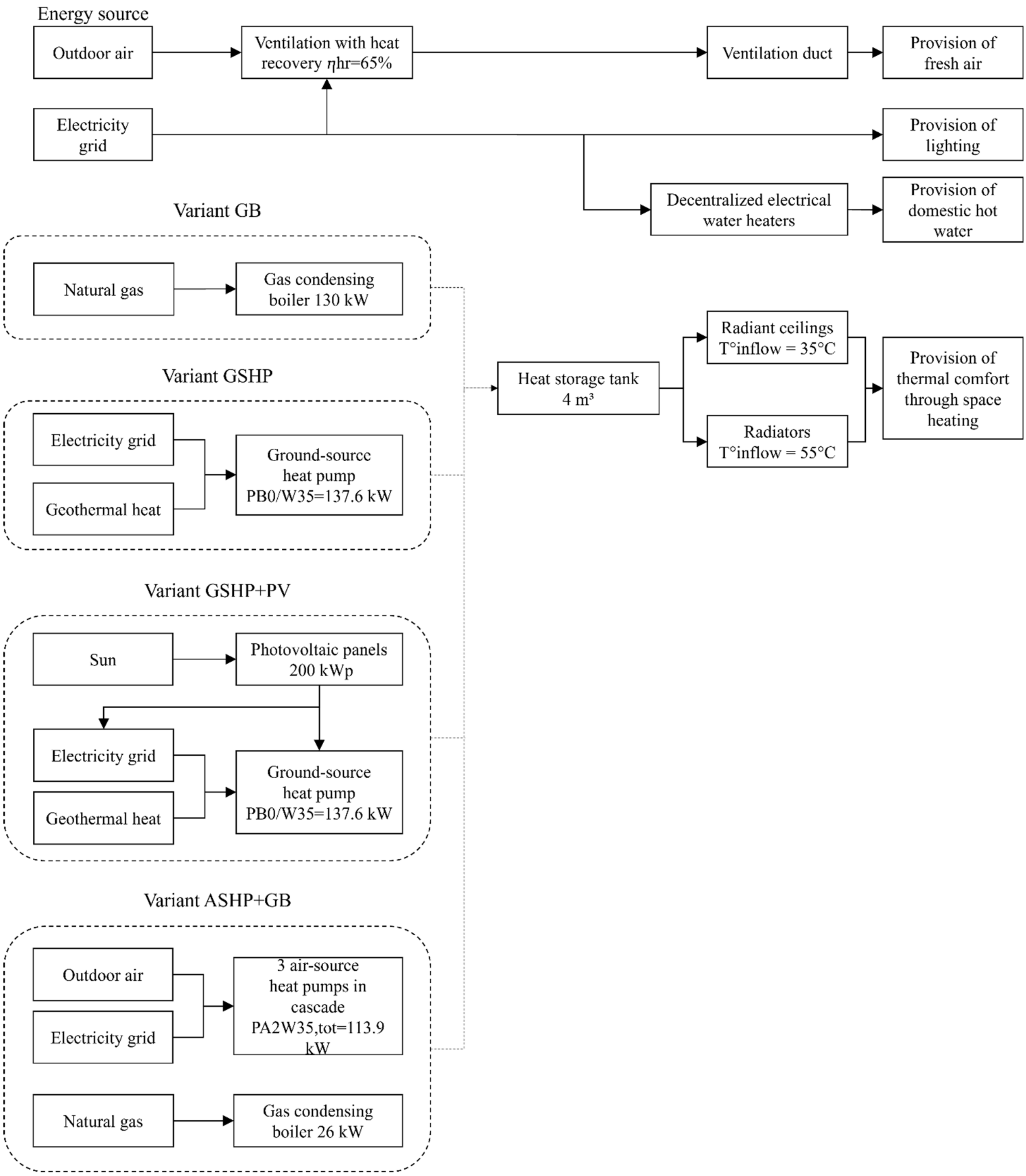

Figure 3. Energy concept and heating system variants.

Domestic hot water (DHW) is provided by decentralized electrical water heaters, which is a common solution for office buildings [48]. A standard DHW consumption of 30 Wh/(m^2·d) was assumed, based on typical values for office buildings. Ventilation was achieved through a centralized system with heat recovery. Plate heat exchangers with a heat recovery rate of η_{hr} = 65% are used. The ventilation provides a standard fresh air input of 4 m^3/(h·m^2) in single and group offices, 6 m^3/(h·m^2) in open-plan offices, 15 m^3/(h·m^2) in meeting rooms, 0.15 m^3/(h·m^2) in ancillary spaces and storage spaces. Sanitary rooms have only air extraction and no air intake. For lighting, an intensity of 500 lx was considered for office rooms, 200 lx for WC and sanitary rooms, 100 lx for ancillary spaces [49], circulation areas and storage rooms, and 75 lx for the parking lot. Table 2 shows the specifications of the heating systems and energy load.

Table 2. Specifications of the heating systems and energy load.

	GB	GSHP	GSHP + PV	ASHP + GB
Heating load (kW)	126.2			
Heat generation system	Monovalent gas boiler	Monoenergetic ground source heat pump	Monoenergetic ground source heat pump	Three air source heat pumps in cascade and gas boiler backup
Efficiency	η_p = 105.5% η_n = 96.5%	$COP_{B\text{-}5W35}$ = 3.9 COP_{B0W35} = 4.6 COP_{B5W35} = 5.2	$COP_{B\text{-}5W35}$ = 3.9 COP_{B0W35} = 4.6 COP_{B5W35} = 5.2	$COP_{A\text{-}7W35}$ = 2.9 COP_{A2W35} = 3.6 COP_{A7W35} = 4
PV generation	no	no	yes	no
Hot water tank capacity (L)	4000			
Ventilation heat recovery rate	65%			
Average heating setpoint temperature (°C)	*18 and 21*			
End energy requirements (kWh/m^2/year)	60.92	25.93	17.04	32.59
Primary energy demand (kWh/m^2/year)	74.61	46.66	30.91	56.47

Notes: GB: Gas boiler, GSHP: ground source heat pump, PV: photovoltaic, ASHP: Air source heat pump, COP: coefficient of performance.

Heat transfer in the conditioned rooms was provided by radiant ceilings and by radiators, depending on the zone type (Table 3). Radiant ceilings enable to minimization of flow and return temperatures of the hydraulic system in the largest heated areas, which leads to the more efficient operation of the heating system and higher thermal comfort [49].

Table 3. Heat distribution systems used for the energy analysis.

Zone Type	Radiators T_{in} = 55 °C/T_{out} = 40 °C	Radiant Ceilings T_{in} = 35 °C/T_{out} = 25 °C
Single office	x	
Group office		x
Open-plan office		x
Meeting and seminar rooms		x
Circulation area	x	
WC and sanitary rooms	x	
Storage, technical areas, archives	x	
Ancillary spaces	x	

3.3. Scope of the Life Cycle Assessment

The scope of the LCA includes the production phase (A1–A3) and transport (A4) of the heating systems according to DIN EN 15804 [31]. In addition, the operational energy of the building is considered (B6 phase according to DIN EN15978 [32]) for a life span of 50 years [50]. Other life cycle phases related to the heating systems such as the end of life (phases C1–C4) are not part of this assessment.

openLCA software [51] is used with the GaBi database [52] for conducting the analysis. The key properties of the heat pump system can be defined as mass, refrigerant use, and coefficient of performance (COP) [53]. Most of the processes of the GSHP and ASHP were available in the GaBi database. The database only provides processes for a 70 kW and a 14 kW heat pump, while the required power is 138 kW and 114 kW respectively. To compensate for this, the LCA results were linearly interpolated in proportion to the power. Moreover, the weights of the devices in kg were interpolated to calculate the impacts of the transportation.

The processes available in the life cycle inventories for the operation of boilers and heat pumps include assumptions on the corresponding efficiency or COP. The average efficiency ratio considered in the database differs from the one required for the case study. To compensate for this difference, a linear interpolation was conducted on the amount of thermal energy required for space heating.

3.3.1. Gas Boiler

The process "Gas condensing boiler 120–400 kW (upright unit) (A1–A3); technology mix; production mix, at the plant; 1 piece (en)" has been considered from the GaBi database. As the gas condensing boiler has a power range from 120 kW to 400 kW no power adaptation was necessary for the calculation. The average weight considered is 973 kg. The efficiency of the boiler is 105% at a partial load of 30%, and the average efficiency of the boiler is 102%, both calculated according to DIN V 4701-10 (2003) [54]. The main inputs are natural gas mix and electricity grid mix. The auxiliary energy demand (electric power) is included in the data set.

For natural gas, the process "Natural gas mix; technology mix; consumption mix, to the consumer; medium pressure level (<1 bar) (en)" has been considered. The data set covers the entire supply chain of natural gas. This includes well drilling, natural gas production, and processing as well as transportation via pipeline. Main technologies such as conventional (primary, secondary, tertiary) and unconventional production (shale gas, tight gas, coal bed methane), both including parameters like energy consumption, transport distances, and gas processing technologies are individually considered for each production country. Natural gas-producing countries, including Germany, contribute by their corresponding shares to the natural gas mix: Russia 39%, Netherlands 29%, Norway 22%, and Germany 10%.

3.3.2. Ground Source Heat Pump

The process "*Electric heat pump (Brine-Water, geothermal probe) 70 kW (EN15804 A1-A3), production mix, at the plant, technology mix, 1 piece*" has been used, which consists of pipelines, probe, ground collector or well and feed line, cooling medium circuit, heating circuit, electronic and casing and expansion tank. For the operation of the GSHP, the process "*Electrical heat pump brine-Water (5/55) (EN15804 B6), production mix, at the plant, technology mix*" has been selected. This process accounts for the generation of thermal energy by a GSHP and the provision of heat to a transmission medium to distribute the heat within the building. With a brine temperature of 5 °C and a flow temperature of 55 °C, the COP is 2.4. Auxiliary electricity demand is included.

3.3.3. Electricity of the Photovoltaic System

The process of "*Electricity from photovoltaic, production mix, at the plant, AC*" is selected from the database. The PV model is based on the global average market mix of photovoltaic technologies installed in 2016. All technologies are modelled individually. The efficiency of the panels is based on specific annual irradiation values averaged for Germany. The manufacturing and operation of the system are considered. Concerning the operation phase, only the PV electricity consumed on-site was considered for the LCA, not the PV electricity fed into the grid system.

3.3.4. Air Source Heat Pump

The process "*Electric heat pump (Air-Water) 14 kW, production mix, at the plant, technology mix, 1 piece*" is selected for the production of the ASHP. The dataset describes the production of an ASHP for space heating with an external heat exchanger and an internal compressor (split device) for low-temperature applications (up to 60 °C). The reference year is 2018. The rated heating power is 14 kW. The COP at 2 °C outside temperature and flow temperature was estimated as 35 °C. Warm water storage tanks and fixing materials have not been accounted for. Regarding the ASHP operation, the process of "*Electrical heat pump brine-Water (5/55) (EN15804 B6); technology mix; production mix, at the plant*" is considered. The same process as for scenario GSHP was used because no dedicated process for ASHP operation was available in the GaBi database.

3.3.5. Transport

The process used for the transport of the heat generation system from the manufacturer to the consumer's location is "Truck (EN15804 A4), consumption mix, diesel driven, Euro 5, cargo, 20–26 t gross weight/17.3 t payload capacity", with a transport distance of 200 km. For variant GSHP + PV, the transport of the PV panel was already included in the process used for characterizing electricity generation from PV. Therefore, only the weight of the heat pump was considered. Table 4 shows the details of the input data for the transport.

Table 4. Input data for transport from manufacturer to consumer, GSHP: ground-source heat pump, ASHP: air-source heat pump, PV: Photovoltaic.

Heating Variant	Power in Database [kW]	Required Power [kW]	Total Device Weight in Database [kg]	Total Interpolated Weight [kg]
Gas condensing boiler (1)	120–400	130	973	973
Gas condensing boiler (2)	20–120	26	283	283
GSHP + PV	70	138	6698	13,395
ASHP	14	114	187	1532

4. Results and Discussion

First, the results of the energy analysis are presented, covering the annual final energy demand for space heating considering the four alternatives of the heating systems. Second, the results of the environmental impacts related to the resource and climate footprints are addressed and discussed.

4.1. Energy Analysis

The annual final energy demand for space heating is shown in Figure 4 for the variants with gas boiler (GB), ground source heat pump with and without photovoltaics (GSHP + PV and GSHP), and air-source heat pump with backup gas boiler (ASHP + GB).

Heat pump-based variants (GSHP, GSHP + PV, and ASHP + GB) require less final energy for their operation than the GB because they make large use of ambient heat from the environment. With the GSHP and GSHP + PV the ambient heat accounts for 78% of the final energy, whereas with the ASHP + GB, it accounts for about two-thirds. The GSHP requires less electrical energy because it has a higher COP than the ASHP. The PV system in variant GSHP + PV generates about 168 MWh/a of electricity, among them about 14 MWh/a are used by the heat pump and 38 MWh/a are consumed for ventilation, domestic hot water, and lighting. The total degree of self-sufficiency for all uses (including electricity for ventilation and lighting) reaches 30.5%. The remaining 117 MWh/a generated by the PV system is fed into the grid. The assumed electricity produced by the PV system is relatively low, mainly for three reasons: First, the angle of the roof is 51°, which is 21° more than the optimal angle of 30°. Second, the roof is not completely oriented in the south direction. Thirdly, the shadows projected by the other buildings were considered to obtain more realistic results for the energy analysis.

4.2. Resource and Climate Footprint Analysis

Figure 5 shows the resource and climate footprints of the four heating systems per FU. The footprints of manufacturing and transport are distributed over the whole lifetime of the heating systems. The material footprint is represented by the TMR.

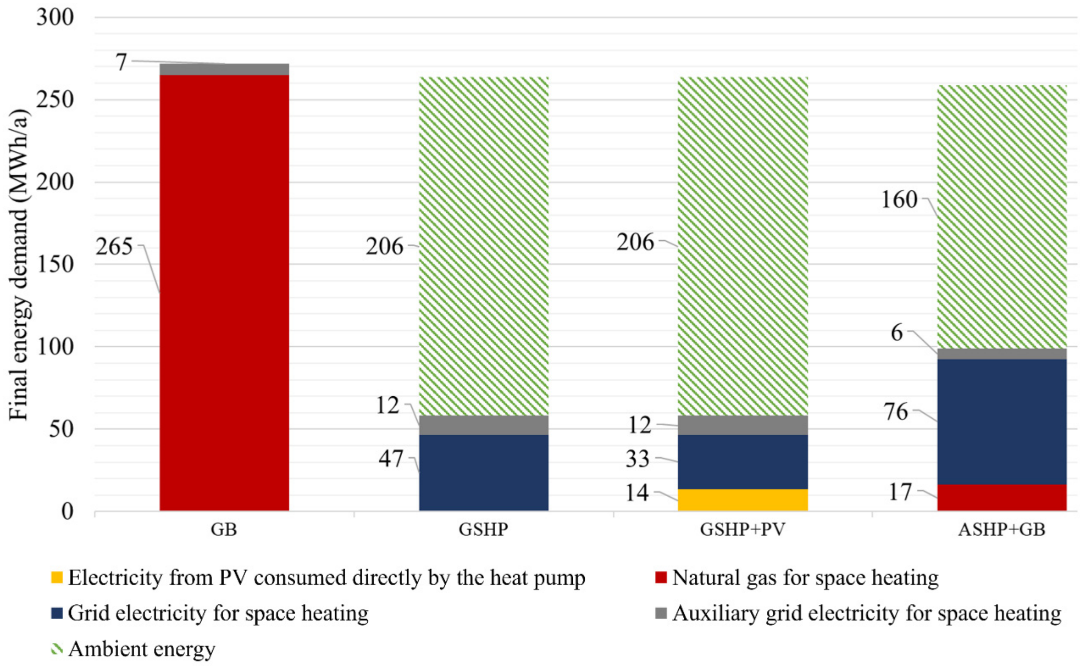

Figure 4. Annual final energy demand for space heating. Notes. GB: Gas boiler, GSHP: Ground-source heat pump, GSHP + PV: Ground-source heat pump with a photovoltaic system, ASHP + GB: Air-source heat pump backed up with a gas boiler.

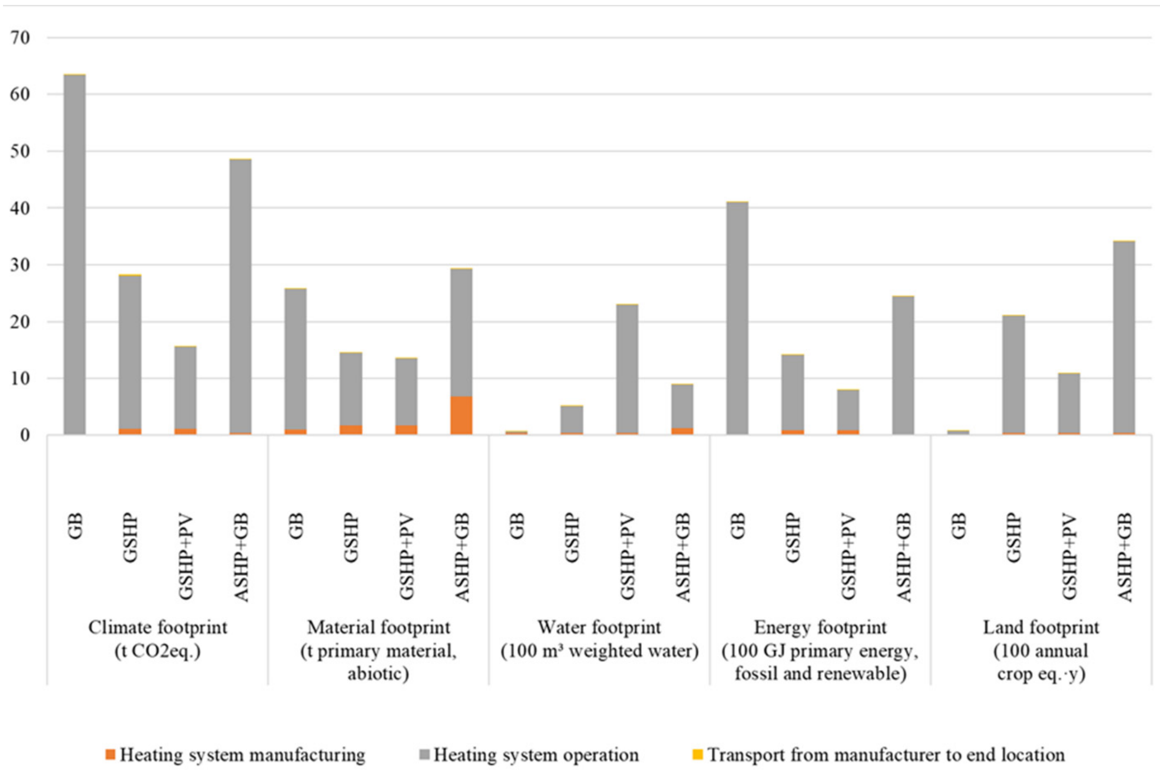

Figure 5. Resource and climate footprints of the four heating systems per final energy for the whole building in MWh per year. The results for manufacturing and transport were applied to the entire service life of 50 years. The material footprint is represented by the Total Material Requirement (TMR). Notes. GB: Gas boiler, GSHP: Ground-source heat pump, GSHP + PV: Ground-source heat pump with a photovoltaic system, ASHP + GB: Air-source heat pump backed up with a gas boiler.

The results show that the operation phase mostly contributes to the footprints of the heat generation system. Transport of the system from the manufacturer to the end-user location causes almost negligible footprints in comparison to the other life-cycle phases.

Variant GSHP + PV can be recommended for its relatively low footprints regarding climate, material, and energy. However, the water footprint of GSHP + PV is relatively high. Regionalized life cycle inventory data shows that most of the water footprint of PV system manufacturing occurs in China, a country with a mainly coal-powered grid. As shown by [55], the amount of water required to produce 1 MWh of electricity from coal is significantly higher than that of other generation technologies. According to the AWARE method, there is 42 times less available water remaining per area in China than the world average [38], while Germany has 1.36 times less available water remaining. In order to improve the performance of the water footprint, the PV panels could be sourced from a country with lower water stress than China, such as Germany.

The relative environmental impacts are represented in Figure 6. The variant with the highest footprint has been attributed with a value of 100% and serves as a reference. For example, the heating system GSHP + PV has the highest water footprint and is then considered as a baseline for this impact category.

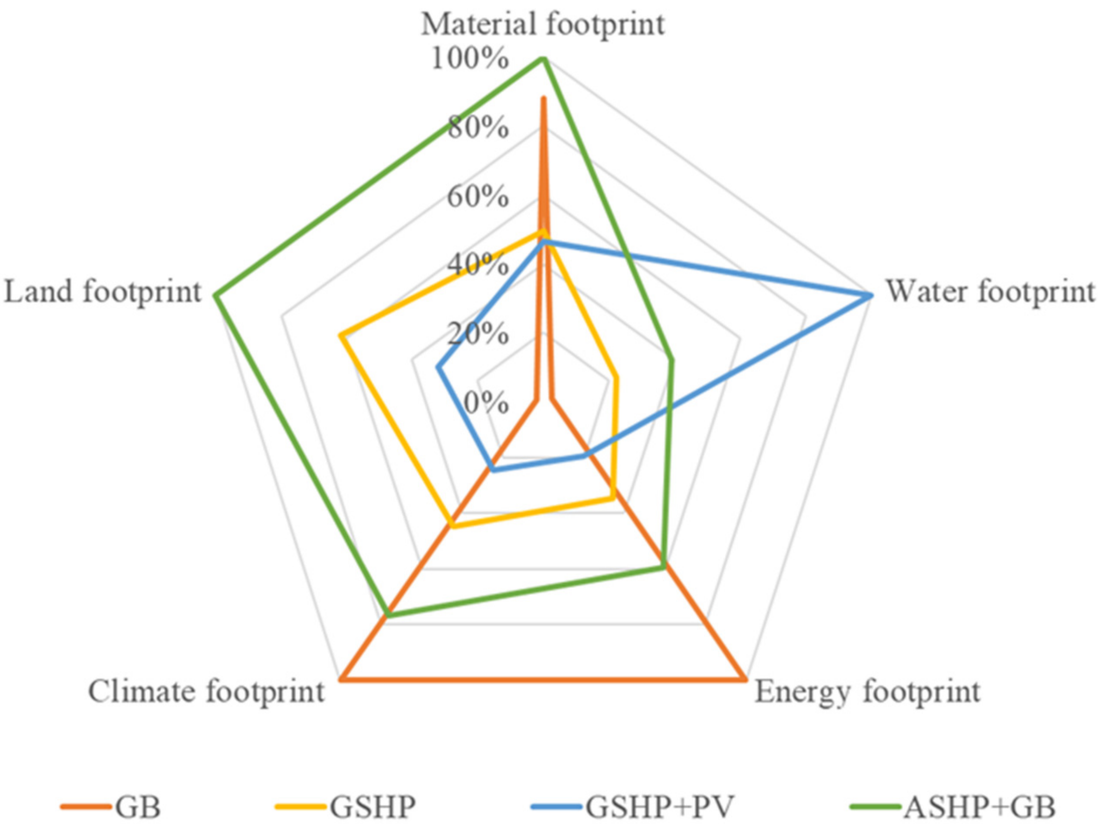

Figure 6. Relative resource and climate footprints of the heating systems. Notes. GB: Gas boiler, GSHP: Ground-source heat pump, GSHP + PV: Ground-source heat pump with a photovoltaic system, ASHP + GB: Air-source heat pump backed up with a gas boiler.

The heating system GB presents the highest impacts in terms of climate and energy footprints and the lowest impacts in terms of water footprint and land use. GSHP has a more balanced impact relative to the others. ASHP + GB has higher footprints than that of the GSHP, due to its lower efficiency, higher electricity demand, and the additional use of a gas boiler. A comparison of variants GSHP and GSHP + PV shows that the use of PV allows a significant reduction in climate, energy, and land footprints, along with a slight reduction of material footprint. This is because the German electricity mix still includes a considerable high percentage of fossil fuels, and the self-consumption of PV-generated electricity reduces the need for grid electricity.

Most of the generated electricity by the PV system is fed into the grid, which can be considered an additional ecological benefit of the use of the PV system. Moreover, heat pumps can participate in grid flexibility, smoothing out peak demand through demand response and facilitating the integration of renewables in the national grid. When choosing a heating system, these additional advantages could be also considered by building planners.

In this assessment, no storage for PV electricity was assumed. If battery storage is considered, the share of self-consumption of renewable electricity could be increased significantly. However, the resource and climate footprints of battery usage should be considered [56].

4.3. Discussion

The resource and climate footprints of heat-pump-based variants are to a large extent dependent on the nature of the electricity consumed by the device. However, the electricity mix in many countries is not static. For example, in Germany, the GHG emissions of the electricity mix have decreased over the past few years, as a result of the increasing development of renewable energies, aiming at reaching carbon neutrality by 2045. The specific GHG emissions of the German electricity mix were evaluated at 401 gCO_2 eq/kWh for 2019 [57] and they should fall below 200 gCO_2 eq/kWh by 2030 if the climate protection targets will be achieved. The LCA results presented by this article are a static view of the footprints, with only one fixed grid mix considered for the whole product life cycle. An approach that is beyond the scope of this work is the dynamic LCA, which can consider the evolution of background technologies and infrastructure and can accordingly account for the changes in the associated environmental impacts.

The LCA highlights a significant difference in water footprint for electricity from the German grid compared to electricity from PV systems. This is due to the weighting done by the characterization factors of the AWARE impact assessment method. As it is weighted by region, 1 m^3 of water withdrawn has a different impact on global water scarcity depending on the withdrawal location. In terms of absolute water consumption from the LCI, 1 kWh produced from the PV system consumes 3.7 times more water than 1 kWh of electricity from the German grid. After applying the regionalized AWARE method to these values, it was concluded that in the case of PV generation, the majority of the water footprint is caused in China, where the raw material extraction and manufacturing of PV panels takes place. These values were obtained after adding up the water scarcity footprints by country. The high footprint allocated to China can be explained by the high characterization factor attributed to this country of 42.43, which is about 31 times higher than that of Germany (1.36).

5. Conclusions

The methodology proposed in this study shows that the combination of BIM with energy analysis and LCA tools could help building planners assess the resource and climate footprints related not only to the use phase of buildings but also to other phases such as production and transport of the heating systems. The methodology was applied to a case study building in Germany. Different heating systems were compared to calculate the energy requirements and the associated material, energy, water, land, and climate footprints. Using a plugin with BIM software for conducting the energy analysis could provide a practical way to design energy systems together with building design modeling. Resource footprints have not been integrated into BIM yet, therefore an additional LCA tool was considered to allow a detailed description of the environmental impacts that are associated with the heating systems.

The results of the case study show that the footprints are mainly caused by the use phase of the building, manufacturing represents less than 12% of the total footprints with a maximum reached for the material footprint of ASHP + GB. The GSHP + PV has the lowest resource and climate footprints with saving potential of 50%, 78%, and 74% in terms of material, energy, and climate respectively in comparison with GB, while the water footprint of GSHP + PV could be comparably high in relation to the water scarcity in the region of the production of PV.

The workflow of the proposed methodology can be improved by developing a plugin within BIM that can exchange data between the LCA and energy calculations such as SURAP [58]. This would significantly simplify the data processing and make the whole methodology accessible for non-LCA specialists at the early building design stage. It could provide a holistic view of the analysis of the building, not only in terms of architectural design and energy requirements but also regarding environmental impacts.

This study is limited to the studied heating systems. For other heating systems such as biomass boilers, the combination of the ASHP with PV and solar thermal collector coupled with GSHP can be considered in future research. A further study can also include a sensitivity analysis of different aspects that improve the energy sufficiency and energy efficiency measures, for instance, improved building insulation or higher technical efficiency of the heating system, and the use of low-temperature heat distribution systems.

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