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" Life cycle assessment of heat pump-based hydronic systems for multi-apartment buildings"

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Abstract

Centralized heat pump (HP) systems are increasingly recognized as a sustainable solution for providing space heating (SH) and domestic hot water (DHW) in multi-apartment buildings. While previous life cycle assessment (LCA) studies highlight the environmental advantages of HP-based systems over conventional technologies, the influence of different hydronic distribution configurations has not yet been systematically investigated. This study conducts a comprehensive LCA of multiple centralized hydronic system variants for a large multi-apartment building with 52 apartments, integrating both embodied and operational impacts. Four configurations are analyzed: (1) a 2+2-pipe system with decentralized fresh water stations (FWS), (2) a 4-pipe circulation system, (3) a 2-pipe system with heat transfer stations (HTS) and (4) a 2-pipe system with decentralized electric boilers. All systems are designed and dimensioned according to conventional engineering rules, with component sizing based on SH loads and DHW profiles. The results indicate that the '2+2-pipe FWS' and '2-pipe HTS' variants exhibit the lowest global warming potential (GWP) over the entire life cycle. The '2-pipe E-Boiler' variant performs the worst of all options, causing at least 30 % higher emissions, even in the optimistic 2040 electricity mix scenario. A key finding is that operating energy has a significant impact on GWP. Under the conditions of the current Austrian electricity mix, the GWP of operation exceeds that of the manufacturing, construction, and disposal phases after around three years, with a magnitude that can be up to nineteen times greater over the entire life cycle.
Overall, the findings emphasize the importance of low-temperature, efficiently dimensioned hydronic systems and high-performance building envelopes. Passive measures that reduce heating demand remain the most effective lever for minimizing life cycle emissions.

Keywords: LCA; HVAC; GWP; distribution system; hydronic system; multi-apartment buildings; fresh water stations;

1. Introduction

The building sector is one of the largest contributors to greenhouse gas (GHG) emissions, accounting for around 34 % of global final energy consumption [1]. As operational emissions continue to decrease, the relative importance of embodied energy is growing. According to [2], the share of embodied GHG emissions has risen from approximately 20 % to almost 45 % of the total life cycle GHG emissions. To assess these impacts comprehensively, a life cycle assessment (LCA) considers every stage of a product's existence from cradle to grave, i.e., from the extraction of the raw materials to their disposal or reuse [EBPD (EU/2024/1275), EN 15978].

Several authors have already performed LCA on the building envelope, e.g., by analyzing different combinations of construction materials. Numerous have compared the life cycle performance of timber, steel and concrete [3]. For example, in [4] it is reported that a multi-story residential building constructed with timber leads to around 30 % fewer embodied emissions compared to one made of reinforced concrete or structural steel, when cradle-to-grave system boundaries (modules A-C acc. to EN 15978) are considered. In several countries, including Saudi Arabia [5] and Iran [6], similar conclusions have been drawn, while a study in Switzerland has investigated the future production of construction materials [7].

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By contrast, substantially fewer studies have focused on HVAC (heating, ventilation and air conditioning) systems. Some research has examined different types of heat pumps (HP). For instance, the authors in [8] compare the energy efficiency of ground source HP with oil- and gas-based heating systems. Other studies have evaluated the environmental performance of refrigerants ([9] and [10]). Notably, the findings in [11] show that by using a refrigerant (R290) with low global warming potential (GWP), the embodied carbon of a HP system with floor heating results in the lowest embodied carbon emission of all considered cases. Furthermore, two different electricity mixes were considered: a medium-carbon (387 g_{CO2eq}/kWh) and a low-carbon electricity mix (75 g_{CO2eq}/kWh). The article states that reducing the carbon emissions of the electricity mix is the most influential factor in reducing overall system emissions.

The impact of emissions during the use phase is significantly higher than the embodied emissions of the HVAC systems. The authors in [12] highlight the critical lack of research on LCA for HVAC systems. The study analyses 36 scenarios for a Canadian residential house with various HVAC configurations and climate zones. It concludes that the sustainability of the electricity mix is a decisive factor, and that combining a HP system with photovoltaics, significantly mitigates the GWP compared to natural gas boilers. While the aforementioned studies address various aspects of the building envelope, construction materials, or heating and cooling technologies, there is a gap in the assessment of the influence of HP system concepts. This is particularly true with regard to different heat distribution systems, which can differ significantly in terms of components (e.g., number/length of pipes, central and decentral buffer store or central or decentral heat exchanger) and also in terms of performance.

1.1. Goal and Scope

Within the Austrian research project “Innsbruck Campagne” different HP system variants are compared in terms of embodied and operational energy using a LCA analysis in order to identify the optimal solution regarding the environmental impact in terms of GWP.

2. Method

2.1. Case Study – Innsbruck Campagne Area

The Campagne Areal project is located to the east of the city of Innsbruck (Tyrol, Austria). It is planned to comprise a total of 1,100 residential units, which will be built in four phases. The first phase, which consists of four buildings (A–D) containing 307 residential units, has already been completed. A central groundwater HP supplies the space heating (SH) demand of these buildings via underfloor heating. Domestic hot water (DHW) is prepared centrally by district heating (DH) and locally by fresh water stations (FWSs). A 2+2 pipe system has been implemented in the first construction phase. This system, shown in Figure 1, requires two pipes for the SH circuit and two for the DHW distribution, consisting of one flow and one return each. An extensive simulation study was conducted during the pre-planning phase, concluding that this heat generation and system choice was optimal in terms of GWP [13].

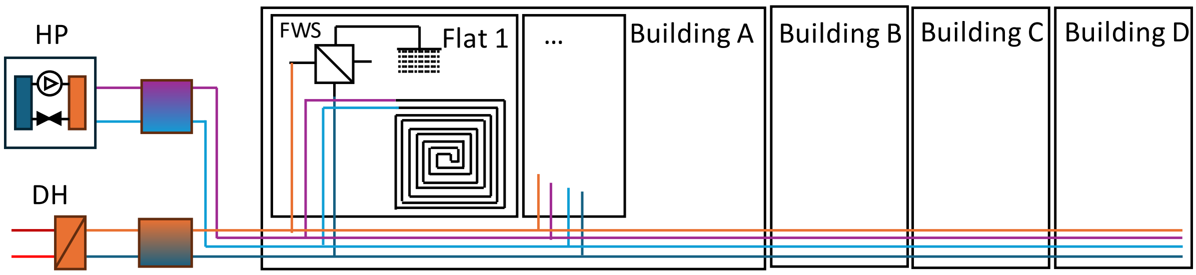

Figure 1. Shows a diagram of the original system (2+2-pipe system supplying four buildings).

2.2. Life Cycle Assessment

The LCA was done according to the EN 15978 standard, which provides calculation rules for assessing the environmental quality of new and existing buildings. The modules introduced in the standard (A, B, C and D) methodically divide the life cycle of a product into phases. The Module A differentiates between the product stage (A1-A3) and the construction stage (A4-A5). It should be noted that the latter is not considered in the LCA presented in this study. Module B describes the use-phase focusing on energy use and service life related repairs and replacements. Module C covers the end-of-life stage, which includes the demolition (C1) and deposing (C4), which are not considered in this study due to uncertainties. Module D allows to include the recycling and recovery potential.

This LCA aims to compare four HP system variants in a multi-stage process. The process begins with a detailed analysis of the existing building technology. In particular, the lengths of the distribution pipes within the buildings are recorded, as these have a significant influence on distribution losses. To ensure comparability, it is assumed that the determined pipe lengths would remain constant for the fictitious variants. They therefore serve as both a basis and a control variable. In the second step, the different system variants are sized. This is done using the existing inventory plans and taking into account hydraulic and thermal parameters. These included pipe diameters, flow and return temperatures, and the nominal capacities/sizes of the relevant HPs, E-Boilers and transfer stations (i.e., heat exchangers).

Unlike the original system, the variants to be compared assume monovalent, building-wise HPs, which were dimensioned accordingly. A LCA is then carried out for each variant, considering not only the final energy demand (FED) and the associated environmental impacts, but also the service life of the individual system components. This enables a realistic assessment of differences in replacement requirements, maintenance and repairs. The FED of the DHW and SH is calculated for a whole year in hourly resolution, using the same method as in [13].

2.3. HVAC Variants

In contrast to the realized system (see Figure 1), it is assumed that heat is supplied entirely by building-wise groundwater HPs. The selected heat emission for SH is an underfloor heating (UFH) with a design flow temperature of 35 °C. The calculations are done for Building C, which has 52 residential units, using the current climate of Innsbruck. The investigated system variants are presented below.

2.3.1. Variant "2+2- pipe FWS" (decentral flatwise FWS + UHF)

Figure 2 shows the adapted 2+2-pipe system with the building-wise groundwater HP. In the 2+2 pipe system, a decentralised FWS for DHW preparation is installed in each flat. The FWS is supplied with a flow temperature of 52 °C and prepares the DHW to 45 °C which is the chosen setpoint for all variants. A hydraulic separator is used in the heating circuit to hydraulically decouple the mass flow of the circulating DHW from that of the heating circuit.

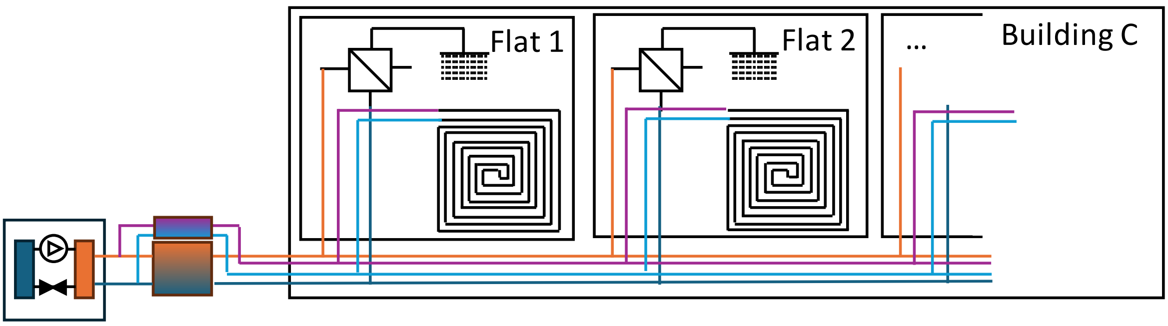

Figure 2. Scheme of "2+2-pipe FWS", distribution system and decentral FWSs.

2.3.2. Variant "4- pipe circulation" (UHF)

The 4-pipe circulation system is a classic distribution system, shown schematically in Figure 3. A central heat exchanger charges a DHW buffer storage tank, which is designed as stratified storage tanks. For hygiene reasons, the temperature of the DHW must be kept high (≥60 °C).

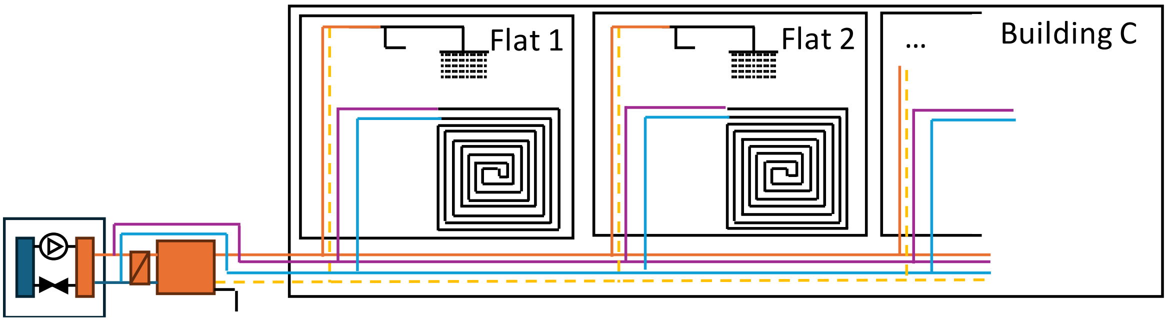

Figure 3. Scheme of "4 pipe circulation", distribution system.

2.3.3. Variant "2-pipe HTS" (decentral flatwise HTS + UHF)

Figure 4 shows the 2-pipe variant. A heating water circuit supplies the heat transfer stations (HTSs), which serves the UFH and prepares the DHW. This combination reduces the amount of material required for distribution. However, the flow temperature is determined by the DHW criteria (≥52 °C). In this design, the common distribution pipe prevents cooling by means of the UFH.

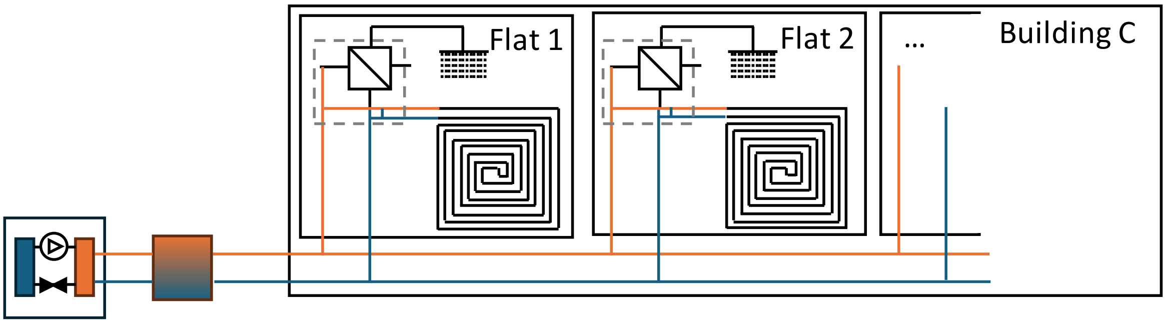

Figure 4. Scheme of "2 pipe HTS", distribution system and decentral HTSs.

2.3.4. Variant "2-pipe E-Boiler" (decentral flatwise E-Boiler + UHF)

Figure 5 shows the 2-pipe plus electric boiler variant. In this variant, a decentralised electric boiler is installed in each flat to provide DHW. In this variant, the HP only covers the SH demand. This enables low flow temperatures (35 °C) during the heating period that increases the HP's COP.

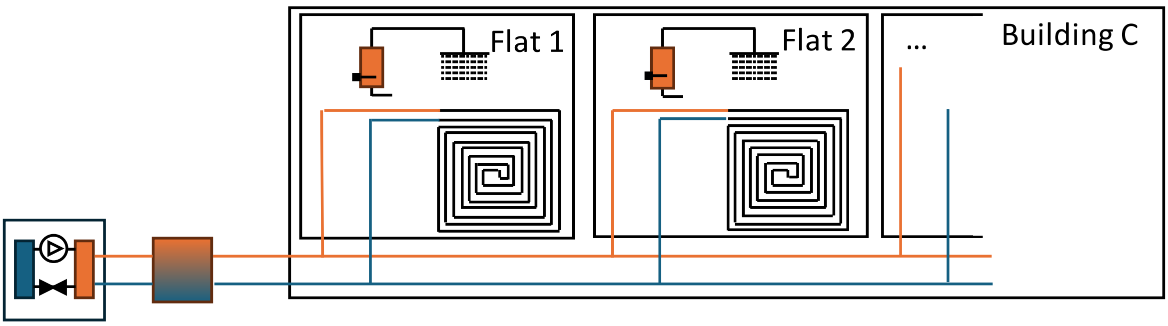

Figure 5. Scheme of "2 pipe E-Boiler", distribution system and decentral E-Boiler.

2.4. Boundary Conditions

The comparison of the system variants does not consider the embodied energy of the entire HVAC, as this would have required the detailed dimensioning of a large number of identical components (e.g., UFH piping). The effects of systematic differences between the variants were the only factors taken into account. Such differences may be exemplified by the dimensioning of HPs of different sizes, changes in pipe diameters with varying pipe lengths, or differing requirements for the central heat supply. It is imperative to note that the critical components which are identical in all variants are not considered in the calculation. These are for example the distribution pipes within the flat or the groundwater well with associated pumps. This facilitates the identification of the pertinent variations between the system variants and the subsequent evaluation of their specific ecological and energetic effects in a transparent manner. Table 1 presents a comprehensive list of the components in- and excluded in the system variants.

Table 1. Included and excluded components of the variants in the LCA.

Included	Excluded
Building-wise groundwater HP	Groundwater well pump
Distribution hydronic system until residential unit	UFH piping system
Distribution and circulation pumps	Distribution within residential unit
Buffer storage	
E-Boilers	
Decentral FWSs and HTSs	
Central FWS	

2.5. Components

The key components of the heat supply and distribution systems are examined in more detail below. The calculation does not include components used across multiple variants (e.g., the technical room) or within individual flats (e.g., UFH, shower mixers and distribution within the flat). The term 'GWP' (Global Warming Potential) is used in the following sections and chapters as an abbreviation for CO_2-equivalent weight in kg to simplify the presentation of climate-related emissions.

2.5.1. Groundwater HP

The Ökobaudat [14] data sets enumerate brine-water HPs with three discrete nominal capacities. These serve as a reference point for the LCA. As Table 2 illustrates, the following data has been utilised for the purpose of evaluating HPs.

Table 2. Nominal capacity, weight and GWP of the individual life cycle phases for brine water HPs [14].

Nominal capacity in kW	A1-A3 in GWP	C2 in GWP	C3 in GWP	C4 in GWP	Sum of A+C in GWP	D in GWP	Mass in kg	Service life in a
20	2073	12.3	4.3	0.1	2090	-126.9	1498	15
70	6513	39.5	11.3	0.2	6564	-215.6	4855	15

The GWP and weight of the HP are determined using linear interpolation of the reference points based on the nominal capacity. Furthermore, the fill quantity and corresponding GWP of the refrigerant must be established. It is assumed that the HP is filled with propane (R290) refrigerant. This refrigerant is listed in the Ökobaudat [14] data sets with a GWP for each kg of the filling quantity. The refrigerant charge is determined using simplified methods and test results from the “Wärmepumpen-Testzentrum Buchs” (WPZ) [15]. As the nominal capacities of the tested HPs are all below the required values for the system variants, the fill quantity of the refrigerant had to be extrapolated. Consequently, the results of this study should be interpreted with appropriate caution.

2.5.2. Distribution Pipes

The sizing of the pipes (e.g., lengths and diameters) was determined in [16] for all variants. The pipes have been insulated with a “3/3” insulation (i.e., minimal thickness of insulations is pipe diameter). Outside the thermal envelope steel pipes are assumed, while inside the thermal envelope composite pipes (PEX–AL– PEX) are assumed. The service life of the pipes is assumed to be 30 years.

2.5.3. Pumps

In this study, a clear distinction is drawn between pumps with a rated power of less than 50 W and more than 50 W to 250 W. The weight and the GWP are specified depending on the rated power. Intermediate values are then subjected to linear interpolation. Table 3 presents the data sets derived from Ökobaudat [14].

Table 3. Rated pump power, weight and GWP of the individual usage phases for circulation and distribution pumps.

Rated pump power in W	A1-A3 in GWP	C2 in GWP	C3 in GWP	C4 in GWP	Sum of A+C in GWP	D in GWP	Mass in kg	Service life in a
< 50	11.1	0.026	0.43	0.026	11.6	-2.02	2.5	15
50–250	22.3	0.053	0.85	0.053	23.2	-4.04	4.9	15

2.5.4. Buffer Storage and E-Boiler

The GWP of the buffer storage is calculated based on the storage volume as nominal size acc. to [14]. The results of the data collection process are presented in Table 4. The material of the buffer storage tank is assumed to be stainless steel, with mineral wool as insulation and a thickness of 10 cm. The decentralised e-boilers (* in Table 4) are assumed to be small buffer storage tanks with a 2 kg stainless steel heating rod.

Table 4. Weight and GWP of the individual usage phases for buffer storages, E-Boiler* and hydraulic separators**.

Net Volume in L	A1-A3 in GWP	C2 in GWP	C3 in GWP	Sum of A+C in GWP	D in GWP	Mass in kg	Service life in a
120*	147	0.2	3.8	147	-25	40	15
165**	188	0.0	1	188	-32	51	30
200**	225	0.3	5.9	226	-39	61	30
1200	693	0.0	2	693	-119	189	30
2000	962	1.1	25.0	964	-165	263	30

2.5.5. Fresh Water Stations and Heat Transfer Stations

The calculation of the individual components and the housing of the FWS is based on the data sheet [17] of the installed FWS ('TA-Comfort-W' from IMI). The mass of the heat exchangers is derived from similar models from the manufacturer SWEP and is determined using the DThermX design tool [18]. For the sake of simplicity, it is assumed that the HTS correspond to the decentralised FWS in terms of mass and material composition, and thus also in terms of GWP. The heat exchanger of the central FWS of the '4-pipe circulation' variant is scaled according to the nominal capacity. Table 5 provides a comprehensive list of the masses and the resulting GWP of the FWS and HTS.

Table 5. Mass in kg and GWP of the central and decentral FWS/HTS.

	Material	Mass in kg	GWP	Service life in a
decentral FWS/HTS	Brass	6.3	8.1	30
	Stainless steel	17.5	57.2	
	-	Σ23.8	Σ65.3	
central FWS	Brass	6.4	8.2	30
	Stainless steel	18.6	60.9	
	-	Σ25.1	Σ69.4	

2.5.6. Equivalent Additional Components

The equivalent additional components combine the remaining smallest components into one share. As demonstrated in [16], they demonstrated a resolute determination. Examples of such valves include e.g., T-pieces, shut-off valves and three-way valves. This resulted in the definition of an equivalent additional component with a mass of 1 kg and a GWP of 2.1 kg. For sake of simplicity, the service life is assumed to be 30 years for all these components.

2.5.7. Component Overview

Table 6 summarizes and shows the components for each HP system variant with the respective nominal size and the case sensitive flow temperature provided by the HP.

Table 6. Overview of components used per variant and their nominal size.

		2+2-pipe FWS	4-pipe circulation	2-pipe HTS	2-pipe E-Boiler
Nominal capacity HP	kW	66	66	66	55
Flow temperature of HP for SH (DHW)	°C	35 (52)	35 (60)	52	35 (-)
Rated power of charging pump	W	50	2*50	50	50
Volume hydraulic separator	l	200	200	0	165
Nominal capacity of central HX	kW	0	66	0	0
Volume of DHW buffer	l	2000 + 1200	2000 + 1200	2000 + 1200	52*120
Rated power of distribution pump	W	2*250	2*250	250	250
Nominal capacity of decentral FWS/HTS	kW	46	0	46	0
Equivalent Additional Pieces	-	486	526	260	260

2.6. Operational Energy

The useful and final energy demand (FED) of the variants was calculated using the calculation model from [13]. The chosen HP for the calculation is modeled with a constant Carnot efficiency of 0.40, assuming a constant source temperature of 10 °C (COP = 4.9 at W10W35). In the hourly calculation the flow temperature of the SH is adapted based on a heating curve. The FED is converted to CO_2 equivalents using conversion factors for various electricity mix scenarios, which are listed in Table 7. To highlight the difference between design values and the actual electricity mix, two scenarios, “OIB 2023” and “EIV”, were applied for the current state. The third scenario allows to consider the influence of an increasingly decarbonized energy system in the future.

Table 7. Conversion factors in GWP per FED of electricity mix scenarios.

Scenario	Description	g/kWh	Source
EIV	Annual mean consumer electricity-mix from Austria 2020 - 2024	173	[19]
OIB 2023	OIB Guideline 6 “Energieeinsparung und Wärmeschutz”, May 2023	156	[20]
AIT 2040	Derived from “Impact Assessment der Europäischen Kommission“ for 2040	56	[21]

3. Results

The results in the following subchapters are divided according to the modules in EN 15978. Please note that "cumulative specific GWP" always refers to the global warming potential in CO_2 equivalent mass per square metre of treated floor area (kg/m_{TFA}^2) i.e., accumulated GWP of first-time installation. "Annual specific GWP" refers to GWP per square meter per year (g/(m_{TFA}^2·a)), where the year value corresponds to the service life of the respective components.

3.1. Embodied energy of HVAC – Module A and C

Combining modules A and C offers the advantage to highlight the impact of a product independent of the use-phase. The results of the LCA of the four investigated variants are shown in Table 8.

Table 8. Results of the LCA in cumulative specific GWP in kg/m_{TFA}^2 and in annual specific GWP in g/(m_{TFA}^2 a).

	Cumulative specific GWP in kg/m_{TFA}^2	Annual specific GWP in g/(m_{TFA}^2a)
2+2-pipe FWS	6.3	268
4-pipe circulation	4.6	212
2-pipe HTS	4.4	206
2-pipe E-Boiler	5.0	301

Table 9 compares the GWP of the four variants by component. The individual components are shown in the respective pie chart in Figure 6. The component shares shown in Figure 6 are color-coded consistently with the colors used in Table 9.

Table 9. Component-specific cumulative specific GWP in kg/m_{TFA}^2 and annual specific GWP in g/(m_{TFA}^2a).

	Cumulative specific GWP in kg/m_{TFA}^2				Annual specific GWP in g/(m_{TFA}^2a)			
	2+2-pipe FWS	4-pipe circulation	2-pipe HTS	2-pipe E-Boiler	2+2-pipe FWS	4-pipe circulation	2-pipe HTS	2-pipe E-Boiler
HP	1.7	1.7	1.7	1.5	115	115	115	97
Distribution pipes	2.6	2.0	0.8	0.8	84	63	29	30
Circulation pumps	0.0	0.0	0.0	0.0	1	2	1	1
FWS/HTS	1.1	0.0	1.1	0.0	38	1	38	0
Buffer storage	0.6	0.6	0.6	2.5	21	21	18	168
Eq. additional components	0.3	0.3	0.2	0.2	9	10	5	5
Total	6.3	4.6	4.4	5.0	269	212	206	301

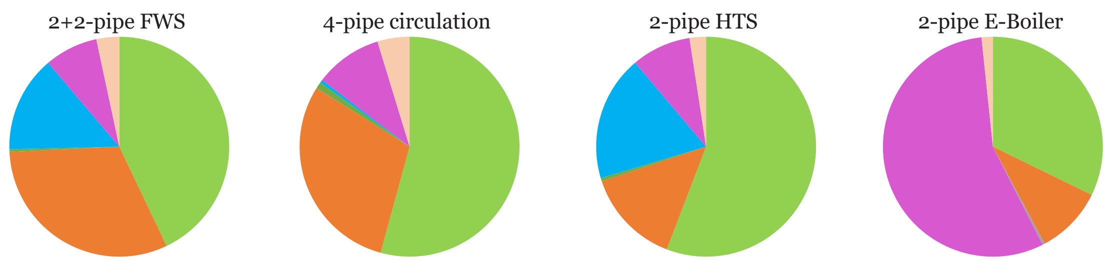

Figure 6. Pie charts of component-specific share of annual specific GWP by modules A + C of the system variants.

3.2. Operational energy of HVAC variants – Module B

Table 10 shows the operating energy of the system variants broken down into the sum of supplied heat (SUP) and final energy demand (FED) with the corresponding proportions for space heating (SH), domestic hot water preparation (DHW), auxiliary energy (AUX) and as a total (SUM). The SH demand (20.1 kWh/(m²a)) and domestic hot water demand (17.8 kWh/(m²a)) are constant for all variants.

Table 10. Operational energy of HVAC variants.

kWh/(m_{TFA}^2a)	2+2-pipe FWS	4-pipe circulation	2-pipe HTS	2-pipe E-Boiler
SUP	53.6	60.3	52.2	42.2
FED_{SH}	4.5	4.3	19.6	5.2
FED_{DHW}	12.3	17.1		20.3
FED_{AUX}	2.8	1.4	2.7	1.4
FED_{SUM}	19.6	22.8	22.3	26.9

Table 11 lists the resulting annual specific GWP of the HVAC variants for the various modules and different conversion factor scenarios.

Table 11. Comparison of Modules A + C with B for varying electricity mix scenarios in annual specific GWP in g/(m_{TFA}^2a).

Life phase according to EN 15978	Electricity mix scenario	2+2-pipe FWS	4-pipe circulation	2-pipe HTS	2-pipe E-Boiler
Module A + C (embodied)	-	268	212	206	301
Module B (operation)	EIV	3391	3944	3841	4654
	OIB 2023	3058	3557	3463	4196
	AIT 2040	1098	1277	1243	1506

Figure 7 shows the relative deviation of the system variants examined compared to the ‘2+2-pipe FWS’ variant, which serves as a reference.

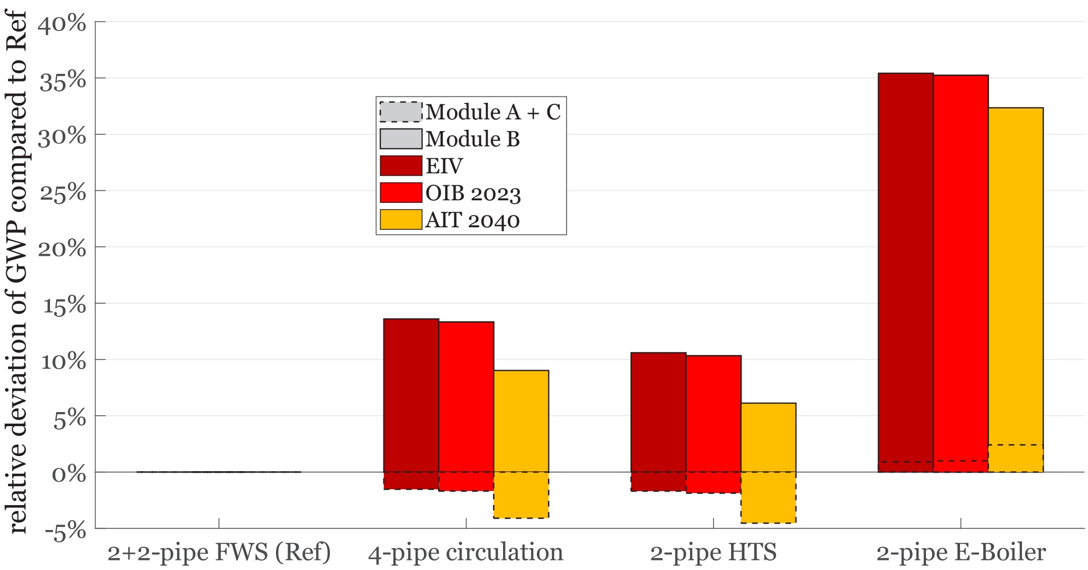

Figure 7. Relative deviation of the system variants depending on the conversion factor scenario compared to the ‘2+2-pipe FWS’ variant as a reference

3.3. Recycling potential of HVAC – Module D

To perform a comprehensive evaluation, it is essential to consider Module D, which relates to recycling and recovery potential. The results that were presented so far have included modules A, B and C. However, it is important to note that the inclusion of module D has the effect of reducing the GWP, on account of the fact that the potential for reuse has a negative contribution in the overall GWP assessment. As illustrated in Figure 8, the calculated embodied energy of modules A and C is represented in green. The proportion that would be deducted from module D is indicated in yellow.

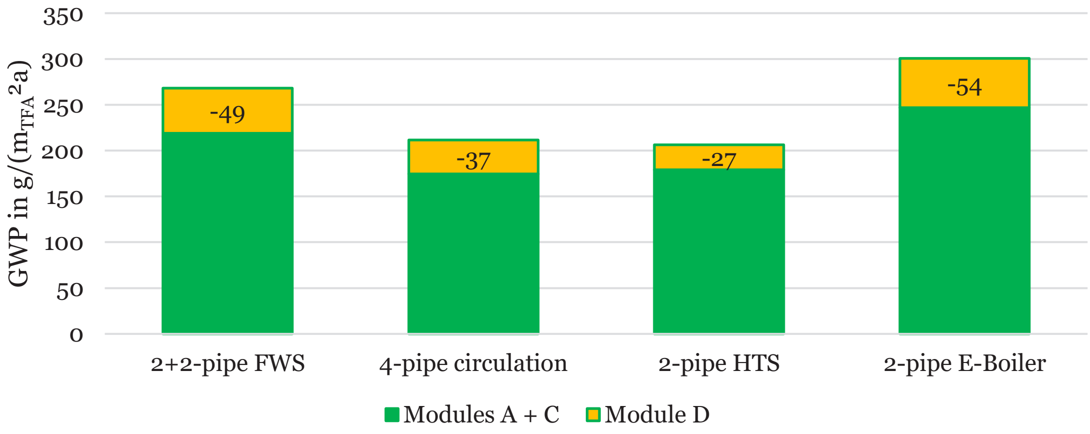

Figure 8. Comparison of the annual specific GWP in g/(m_{TFA}^2a) of modules A+C and reduction through module D

4. Discussion

The findings of modules A and C clearly show that the '2+2-pipe FWS' variant possesses the highest cumulative GWP (see Table 8). The '2-pipe HTS' variant has a significantly lower GWP, closely followed by the '4-pipe circulation' variant. It is evident that the influence of additional distribution pipes on the GWP is comparable to that of the HTSs. Despite the utilisation of smaller distribution systems and lower HP capacities in the decentralised electric boiler variant (see Table 9), the total emissions are higher. The impact of service life is an important consideration. A reduced service life of the electric boilers and the consequent necessity for replacement within the specified timeframe results in an elevated annual GWP for this configuration in comparison to the '2+2-pipe FWS'.

A comparison of modules A + C with module B (see Table 11) demonstrates that operation (even under an optimistic electricity mix scenario for 2040) has approximately five times the impact on GWP as the embodied energy of the system (ranging from 4.1 to 6.0). In the context of the prevailing electricity mix conditions, this ratio ranges from approximately 13 to 19. Given that the average service life of these systems is less than 30 years, it can be calculated that after less than three years of operation (based on today's electricity mix), the use phase will exceed the GWP of manufacturing, construction and disposal. It is also noteworthy that the example building examined exceeds the current new building standard with regard to energy efficiency.

As demonstrated in Figure 7, which presents a comparison of the variants with the reference ('2+2-pipe FWS'), all of the HVAC variants result in higher annual GWP for every scenario. In the most favourable circumstance, the '2-pipe HTS' variant (with AIT2040 electricity mix) exhibits a GWP that is approximately 6 % higher, a consequence of the elevated DHW supply temperature. Additionally, it should be mentioned that the '2-pipe HTS' variant cannot be used for cooling, in contrast to the other variants. The '2-pipe E-boiler' variant performs the worst in comparison; even in the 'AIT 2040' scenario, its annual GWP is at least 30 % higher than the alternatives.

Depending on its material, the recycling and recovery potential of a component can have a significant impact on the GWP. However, given the uncertainty surrounding future forecasts, the reduction potential of Module D is presented separately. In principle, a significant proportion of system components can be categorised according to their type and thus rendered readily recyclable. This represents a notable advantage over conventional building materials.

5. Conclusions

The decarbonisation of the building sector heavily depends on the creation of durable and energy-efficient buildings with well-dimensioned HVAC systems. Passive measures, such as the implementation of an enhanced thermal envelope or the incorporation of more efficient windows, have been shown to have a significant role on reducing emissions during the use phase.

The choice of HVAC system has a significant impact on the required flow temperatures and the overall energy consumption. Decentralised DHW preparation with FWS enables lower flow temperatures, thereby enhancing HP efficiency while maintaining cooling capability. However, preparing DHW via decentralised electric boilers increases final energy demand by 37% compared to the '2+2-pipe FWS' system.

The findings of the LCA presented in this study further clarify that smaller components, such as pumps or fittings, have little impact on the overall outcome. Generally, the level of embodied energy is approximately one order of magnitude lower than that of operating energy. This ratio is subject to change in line with the ongoing decarbonisation of the electricity mix; however, it is anticipated that operating energy will continue to dominate the embodied energy in the future, partly due to the fact that future plant technologies will also benefit from the improved energy mix.

The comprehensive documentation of all components continues to present a significant challenge, as databases frequently exhibit incompleteness and necessitate meticulous dimensional analysis. This approach is both time-consuming and costly during the preliminary planning stages. The utilisation of standardised methodologies and the establishment of comprehensive databases could significantly facilitate the estimation of GWP values in the future.

In summary, it is evident that embodied energy exerts a negligible influence under prevailing conditions, while operating energy is imperative for achieving the desired outcome.

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