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Holistic analysis on domestic hot water preparation concepts with decentral heat interface units

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Abstract

Domestic hot water (DHW) production remains a critical end-use in buildings, particularly for cleaning and hygiene. As advances in building-envelope insulation continue to lower space heating demand, especially in new construction and retrofits, the relative share of DHW in total heat demand is steadily rising, reaching up to 55% in highly efficient buildings. This growing proportion underscores the substantial potential of DHW systems for energy-saving measures and high-efficiency design, while still meeting stringent hygiene standards and occupant comfort requirements.

This paper shows an experimental investigation on different hydraulics, regarding the DHW preparation and its influence on the efficiency of a heat pump heating system. Two decentralized concepts, one with a heat interface unit and one with an instantaneous water heater, are investigated. As a benchmark or state-of-the-art concept, a centralized DHW preparation with circulation line is examined.

The three variants are evaluated in terms of energy efficiency by means of experimental system tests based on reference days on a test bench. The test cycles and load profiles used last several days. An economic and ecological evaluation is carried out for the concepts. Economic efficiency is assessed by using the annuity method of depreciation. Ecological efficiency is evaluated in terms of whole life carbon emissions. The energy savings, the CO_2 savings potential and the whole life carbon emissions are compared and evaluated to the reference case.

The study underscores the substantial potential of decentralized DHW concepts to enhance energy efficiency while delivering notable ecological and economic benefits.

Keywords: Decentral Heat Interface Units; Heat-Pump Heating System; Whole Life Carbon Emissions (WLCE); Experimental Study; Multi-Storey Residential Building; Retrofit;

1. Introduction

The German building sector was accounted for about 30% of all CO_2 emissions and a share of 36% of the total final energy consumption in 2021 [1]. Hence, retrofitting the building stock offers great potential for both energy savings and CO_2 reduction. In addition, the already emitted CO_2 during the construction of the building stock can be conserved by retrofitting the building instead of demolishing and re-building it.

In general, the overall heat demand of such a building is the combination of space heating (SH) and domestic hot water (DHW) demand. The preparation of DHW is crucial for everyday life applications and uses, where a need for hot water is required (e.g., cleaning or showering). Lower supply temperatures and reduced heating demand requirements are to be expected, particularly in new buildings and retrofits, due to advances in insulation of the building envelope. In contrast, higher temperatures are always required for DHW preparation, meaning that the relative share of DHW of a building's total heat demand will gradually increase. In the German

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building stock of 2023, DHW accounts for around 24% of the total heat demand on average [2]. In contrast, the share of DHW in newly built or refurbished buildings reaches values up to 55% [3-4]. A review on energy-efficient DHW systems showed a steady increase of the share of final energy used for DHW preparation in residential buildings in Denmark, France and Spain in respect to their year of construction [5]. Especially in recent years the share rises to around 40%. DHW is often energy-intensive [5-6]. The German per capita daily water consumption in 2021 was 127 liters, which has changed only marginally since 2015 [7]. However, DHW demand rose gradually by around 24% during the same period [8]. In addition, large centralized DHW systems generally can exhibit high heat losses of between 23-70% due to circulation, distribution and stand-by storage losses, which also limit the efficiency of the heating system [4,6]. Therefore, DHW is considered to offer enormous potential for energy-saving measures and energy efficient system designs, while still complying with legal hygiene and user comfort requirements.

A climate-neutral building standard for the decarbonization of the full range of building types (new and existing, residential and non-residential buildings) is essential for achieving the global climate protection targets [9]. This also involves covering the building's heating demand entirely from renewable energy sources. In new buildings and retrofits, heat pumps (HP) are increasingly becoming the central and, in some cases, sole source of heat [10]. Particularly in combination with low-temperature SH systems, such as underfloor heating, which operates at supply temperatures at approximately 30-40 °C, efficient operation of the heating system can be achieved. Mainly due to improved building insulation, the reduced SH demand and thus, the lower supply temperatures offer substantial opportunities for such renewable heat generators. In contrast, large DHW systems require supply temperatures up to 60 °C with a return temperature not lower than 55 °C to ensure legal hygiene safety requirements [11], which limits the efficiency of a heat pump heating system (HPHS).

High standards are set worldwide for drinking water hygiene, especially regarding the spread of legionella bacteria [11]. The bacteria, in particular *legionella pneumophila*, are found in natural environment as well as engineered/artificial water systems, where they can become a health risk when inhaled via water aerosols (e.g., in showers or bathtubs) [12]. Inhalation in high concentrations or in people with weakened immune systems can cause serious respiratory infections such as Legionnaires' disease. Favourable conditions for legionella growth are water temperatures in the range of 25-45 °C [12-13], like in DHW systems, or pipe segments with stagnant water. The annual notification rate of Legionnaires' disease has been steadily increasing in the EU since 2014 with the highest amount observed in 2021 at 2.4 cases per 100.000 population [13-14]. Four countries (Italy, France, Spain and Germany) accounted for three-quarters of all cases [13].

Maintaining appropriate water temperatures in large DHW systems is the fundamental principle to prevent water hygiene issues [11], whereby measures to increase the energy efficiency of the heating system can have no significant effect. To overcome this limitation, DHW can be prepared decentralized, e.g., via heat interface units (HIU). In recent years, energy efficiency measures and hygiene considerations have led to steady growth in the market for and research interest in HIU [15-18], particularly for the use in multi-storey residential buildings. The need to store a large amount of DHW centrally as well as hygiene problems are eliminated by preparing DHW decentralized in each individual apartment as needed. In addition, HIU offer the structural advantage of reducing the number of supply pipes from four to a minimum of only two, which reduces heat distribution losses and installation effort.

Within the research project "sEnSys", carried out under the supervision of Ohm, an energy supply concept for multi-storey residential buildings, that achieve energy and climate neutrality, is being developed and implemented in a real demonstration building [19]. The concept focuses on energy-efficient, resilient and smart building technologies, a predictive control strategy and cost-effective operation via suitable operator models. For the DHW preparation HIU will be installed. In the framework of this project, this paper focuses on a holistic (energetic, economic and ecological) analysis of DHW preparation concepts with HIU in combination with a HPHS by means of experiments on a test bench. This paper analyses the efficiency of a HPHS using test cycles and load profiles lasting several days regarding three different hydraulic implementations of the DHW preparation (centralized, decentralized, fully electric). These experiments form the basis for energetic, economic, and ecological evaluation based on key performance indicators derived from energy balances, the annuity method of depreciation and the whole life carbon emissions (WLCE), respectively.

2. Methods

2.1. Smart Energy Bench

The experimental study is carried out on the Hardware-in-the-Loop test bench for innovative heating systems (“Smart Energy Bench”, SEB), which combines several heat generation units, thermal energy storage systems (TES), battery energy storage systems and a HIU with a software-driven controlling unit, which can handle a real-time simulation of the system's digital twin. The SH demand, the DHW demand and the source temperature of the HP are emulated by fixed load profiles. The Hardware-in-the-Loop concept ensures a flexible, dynamic and realistic investigation of one single component or the whole HPHS.

This study uses a brine-to-water HP in combination with a 500 liters buffer tank. The HP operates monoenergetic and exhibits a nominal heating capacity of 10.9 kW with a coefficient of performance of 4.9 (at B0W35). Throughout the experimental study, standard manufacturer's settings for the HP internal controller are set. The evaporator of the HP is provided with almost constant temperatures of 10 °C throughout the experiments.

The test bench and its main hardware components used for this contribution can be seen in Figure 1.a. Differences in the hydraulic design of the three different DHW variants and their respective hardware components are discussed in more detail in section 2.2.

Appropriate sensors are installed throughout the test bench for a detailed evaluation of the thermal behavior of the HPHS and its energy flows, as can be seen in Fig. 2. The outgoing heating demand as well as the heating load delivered to the TES can be assessed separately. The electrical power of the HP and any device for DHW preparation is measured by energy meters. In addition, three temperature probes are installed equally spaced over the height inside the TES, to estimate its state of charge or storage stratification.

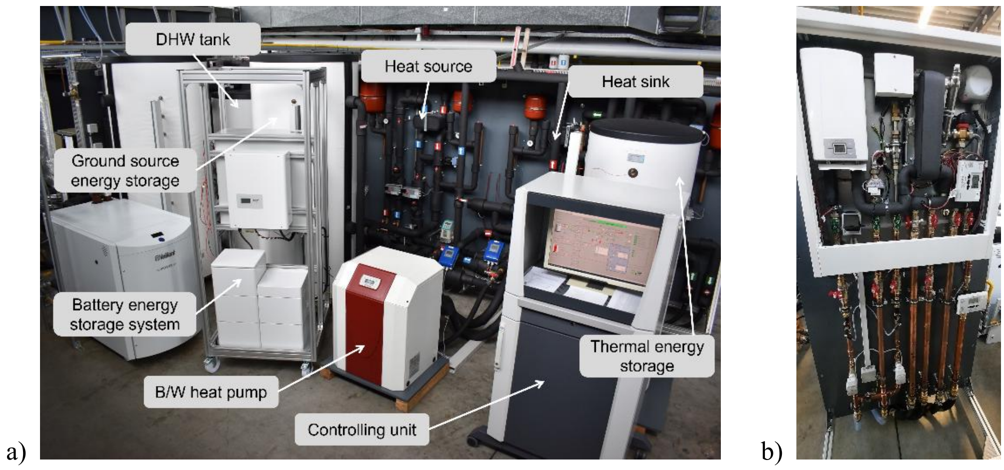

Figure 1. Hardware-in-the-Loop test bench for innovative heating systems ("Smart Energy Bench", SEB) at Ohm (a) and fully integrated decentral heat interface unit with electrical instantaneous water heater (b).

2.2. Hydraulic implementation on DHW preparation

This study examines different hydraulic concepts for DHW preparation. All three concepts use the monoenergetic heat supply from the brine-to-water HP described in section 2.1. Three variants of DHW preparation are considered as follows:

- Variant 1: Decentralized via HIU
- Variant 2: Decentralized via electrical instantaneous water heater
- Variant 3: Centralized with circulation line

Their respective hydraulic schemas and the installed sensors can be seen in Fig. 2.

In variant 1, the HIU in use (c.f. Fig. 1) is supplied with heat directly via the TES by a two-pipe connection (flow and return line) and with pot water (PW). A plate heat exchanger integrated in the HIU pre-heats the pot water to a certain temperature (e.g., 42 °C; minimal comfort requirement; set via a thermostatic valve). Additionally, an electrically driven instantaneous water heater (IWH) with an electrical capacity of 13 kW post-heats the pot water to the temperature set by the user for higher comfort requirements (T_{PWH}; e.g., 45 °C). The flow and return lines are routed through the HIU unmixed and unregulated (no thermostatic valves and/or heating circuit distributors installed). Thus, radiators with supply temperatures of 40-45 °C ($T_{\mathrm{SH,FL}}$) are assumed in the emulated building. The brine-to-water HP operates on a fixed return line temperature set point of 45 °C ($T_{\mathrm{cond,RL}}$), which allows a maximum temperature of approximately 52 °C ($T_{\mathrm{cond,FL}}$) can be achieved in the flow line and TES, respectively. The three-way valve after the TES constantly mixes the flow line temperature of the supply line to 45 °C ($T_{\mathrm{SL,FL}}$) at a volume flow rate of 10 l/min.

An IWH replaces the HIU in variant 2, which represents an electric-only decentralized DHW preparation with maximum electrical capacity of 21 kW. The supply/heating circuit, which is totally uninfluenced by DHW tappings in this concept, features the constraints and boundary conditions set in variant 1. The desired port water temperature (T_{PWH}) at the outlet of the IWH is also set to 45 °C.

As a benchmark or state-of-the-art concept, a centralized DHW preparation is examined in variant 3. The buffer tank of variant 1 and 2 is replaced by a 500 liters combined buffer storage tank, where cold pot water (PWC) is heated by an internally installed tube heat exchanger. In addition, a circulation line is implemented with a regulated fixed temperature spread of 3 K, to emulate circulation heat losses. Due to constructional restrictions, the supply line for the SH, like the HP, is connected to the "primary side" of the TES. If there is SH demand either the HP or the TES can deliver sufficient heat. The HP return line temperature set point is 65 °C, to disable the HPs' internal controls. As the return line temperature of the HP no longer necessarily corresponds to the storage tank temperature in this design, a bang-bang controller with a hysteresis of 2 K is implemented in the software. An average TES temperature lower than 58 °C triggers a request to charge the TES and starts the HP respectively. This enables temperatures up to 60 °C in the TES. Such high temperatures are necessary for most large centralized DHW systems to ensure hygiene safety requirements. This variant has no built-in thermostatic DHW mixing valve. To emulate such a mixing valve, energetic tapping is implemented rather than volumetric tapping as in variant 1-2. Although less pot water is drawn, a comparable amount of energy is used from the TES.

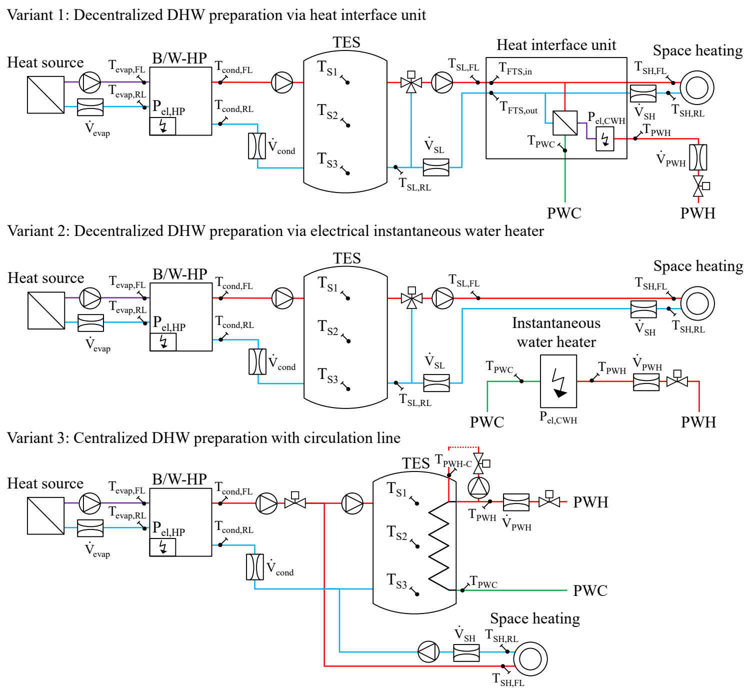

Figure 2. Hydraulic schemas of the Hardware-in-the-Loop test bench for the three considered concepts for DHW preparation.

2.3. Energetic assessment

By means of experimental system tests based on reference days an energetic assessment of the three variants is carried out on the test bench. Therefore, an apartment of a multi-family house is emulated over a period of two consecutive days. Standardized SH load and DHW tapping profiles are utilized. In addition, a PV system is assumed. An assessment is performed based on various key performance indicators, such as final energy demand, system performance factor (SPF), load cover factor (LCF) and supply cover factor (SCF).

Typical reference days in accordance with VDI 4655 [20] are applied to emulate the SH load. This German guideline defines ten reference days (4 winter days, 4 days in the transition period, 2 summer days), two of which are used (one typical summer and winter day each) in the experiments. The selected reference winter day features an almost constant SH demand of 0.26 kW throughout the day. The selected reference summer day exhibits no SH load. The SH load profiles can be seen in Fig. 3. The heated floor area and the annual specific space heating load of the apartment are assumed to be 75 m² and 14 kWh/m², respectively.

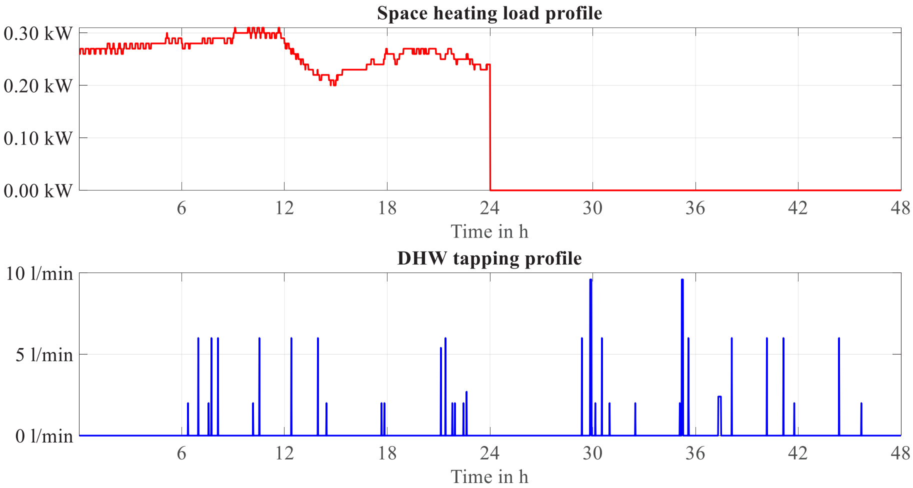

Figure 3. Space heating load and domestic hot water tapping profiles.

The DHW tapping profile is calculated via the software tool DHWCalc [21] for a 3-person household with an average DHW consumption of 40 liters per person per day. The tappings are subdivided into four different categories, which differ in terms of their tapping volume, distribution, and frequency. This enables the emulation of small (e.g., hand washing), medium (e.g., showering), or larger withdrawals (e.g., simultaneous use). The reference winter and summer days feature an overall tapping volume of 68.1 liters and 176.1 liters, respectively, resulting in an average daily tapping volume of 122 liters. The DHW tapping profile can be seen in Fig. 3.

Despite only one of 32 apartments in a multi-family house (c.f. [19]) being emulated, a PV system is assumed. Its size corresponds to the maximum PV system that can be installed on the building's roof divided by the number of apartments. Therefore, each apartment features a PV system with a peak load of 3.13 kWp. The reference PV load profiles in accordance with VDI 4655 [20] are scaled correspondingly to this peak load. Similar reference days were selected as for the SH load profile. The summer day features a load of up to 2.94 kW and a useful energy gain of 17.2 kWh. The total useful energy gain over the two consecutive days amounts so 20.3 kWh. The resulting PV load profile can be seen in Fig. 4.

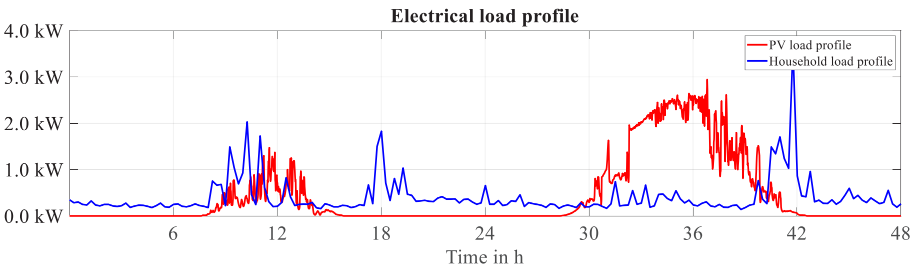

Figure 4. Hydraulic schemas of the Hardware-in-the-Loop test bench for the three considered concepts for DHW preparation.

In addition to the HP's electrical energy consumption, a household load profile is mandatory, to evaluate the PV self-consumption or the operational costs. In combination with the PV load a surplus in the electrical energy of the apartment can occur. The household load profile is based on measured data of one household of a multi-family terraced house with three inhabitants. The load profile features peak loads up to 3.6 kW and a baseload of approximately 0.2 kW. The total household energy consumption is 19.6 kWh. The household load profile can be seen in Fig. 4.

Following the two-day measurement, the energy-related parameters are extrapolated to annual values to evaluate a whole operating year. Therefore, the two reference days are evaluated separately. Two assumptions were made for the extrapolation: The extrapolated heating energy should correspond to the annual heating demand of the apartment (1050 kWh/a), and an average daily DHW tapping rate of 120 liters should be achieved. The reference winter day appears 83 times in the reference year and accounts for 50% of the annual heating demand in the heating period. Thus, 166 of those reference winter days account for the total annual heating demand of the apartment. Consequently, 199 reference summer days complete one year. To achieve a daily DHW tapping rate of approximately 120 liters 189 reference winter and 176 reference summer days are necessary. Finally, the energy-related parameters of each reference day are extrapolated by the average value of each assumption with 178 and 187 for the reference winter and summer day, respectively.

2.4. Economic assessment

The economic efficiency of the different hydraulic concepts for DHW preparation is assessed by using the annuity method of depreciation in accordance with the German guideline VDI 2067 [22]. The annuity method is a dynamic calculation method that takes the whole service life of a component into account. All incoming and outgoing costs (capital-related costs, operation-related costs, demand-related costs, proceeds) of the heating system are distributed evenly over a defined observation period (20 years). The annuities presented in this study represent the annual costs. The most advantageous variant is that with the lowest annual costs, as it is associated with the lowest ongoing costs in general.

The investment (*capital-related*) costs for the HPHS components are derived from existing offers and manufacturer catalogues. The *demand-related* costs (mainly electricity demand from the grid and PV surplus proceeds) can be derived from the energetic assessment data extrapolated to one year (c.f., chapter 2.4) and scaled up to the living-lab demonstrator (32 apartments). The electricity costs for grid consumption are set to 0.316 €/kWh and that for PV surplus proceeds to 0.0636 €/kWh (all prices from 10/2024). The *operation-related* costs are determined in accordance with VDI 2067 for the specific system component. The service life of various components can be derived from this guideline as well (e.g., 10 years for auxiliary pumps, 20 years for the HP, TES and HIU, 40 years for piping). Subsidies or fundings can play a decisive role in the economic assessment, as they can reduce the investment costs of the components and lower the follow-up costs for the owner or tenant. Both are not considered in this study. The interest rate is assumed to be 2.13% and all dynamic interest rates to be 2%.

For the economic assessment, we assume a retrofit of the whole heating system of the living-lab demonstrator within the project “sEnSys” [19]. This includes the installation of a brine-to-water HP with sufficient geothermal probes, a TES, auxiliary pumps, piping and insulation as well as the PV system. Depending on the hydraulic variant, the specific components (e.g., HIU, IWH, and circulation pump) are considered as well.

2.5. Whole Life Carbon Emissions

A comprehensive environmental/ecological assessment requires consideration of the entire life cycle of a system and its components. Thus, production, transportation, installation, operation and disposal of a component must be evaluated in terms of carbon dioxide (CO_2) equivalent emissions, which are referred to as the whole life carbon emissions (WLCE). These CO_2-equivalent emissions are also referred to as the global warming potential (GWP). The GWP describes the climate impact of a certain amount of greenhouse gas compared to the impact of the same amount of CO_2. In building technology and retrofit, the GWP value is used to assess the environmental impact of different building materials and technologies and can lead to more sustainable decisions.

Appropriate emission values for building materials or system components are obtained from a database of the German Federal Ministry for Housing, Urban Development and Building for the life cycle assessment of buildings [23]. The database provides comprehensive CO_2-equivalent emissions divided into five different categories that describe the entire life cycle of a product. For the operation-related CO_2-equivalent emissions the primary energy demand of the system is utilized. Therefore, the final energy demand, determined in the energetic assessment (c.f., chapter 2.4.), is multiplied with the primary energy factor (1.8). One kWh of electricity from the grid accounts for a CO_2-equivalent of 0.56 kg.

The assessment of the WLCE is also related to the living-lab demonstrator mentioned in chapter 2.5., and thus, includes all components for installing the specific hydraulic variant.

3. Results

3.1. Energetic assessment

Several experimental runs (a minimum of two) were performed for each variant. These were carried out under conditions that were as identical as possible (e.g., identical TES starting temperature, pre-heated piping).

They were used to check the reproducibility of the results and confirm the reliability of the measurement data. The data of the individual experimental runs of a variant exhibit only minor deviation from one another. The energetic data presented in this section is the average values of all experimental runs performed for a given variant. All three variants are compared with and without regarding a PV system.

Variant 2 exhibits favourable energetic characteristics in terms of the final energy consumption, as can be seen in Fig. 5. At 6,719 kWh, variant 2 exhibits the least final energy consumption compared to the other variants without PV. 7,442 kWh and 9,278 kWh can be determined for variants 1 and 3, respectively. Thus, the decentralized concept features 38% (variant 2) and 25% (variant 1) higher final energy consumption as the decentralized concepts. In general, the final energy consumption (grid consumption) can be lowered significantly by regarding the installation of a PV system. Variants 1 and 2 exhibit a comparable amount of final energy consumption. Variant 1 amounts to 6,002 kWh and variant 2 to 5,542 kWh. Compared to variant 3 (7,709 kWh), the final energy consumption is approximately 30% higher than in the decentralized variants.

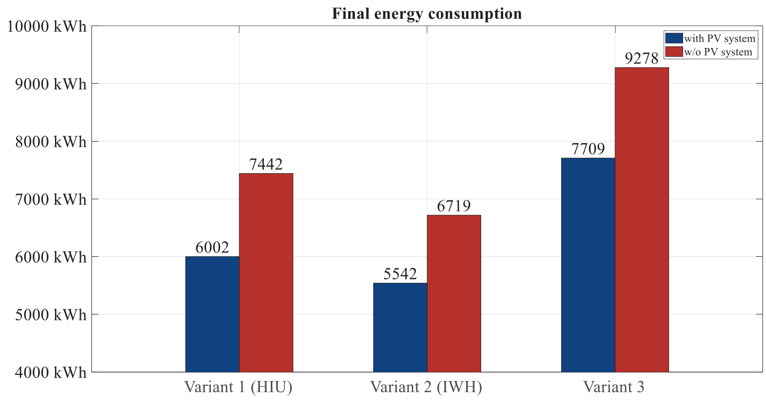

Figure 5. Final energy consumption for the three hydraulic concepts with and without PV system.

The SCF describes the fraction of PV generation, which is consumed directly within the building (residential or HP electricity). Variant 3 accounts for the highest share of SCF at 42.1%. A similarly high share of SCF, at 38.6%, can be achieved with variant 1. Variant 2 features the lowest SCF at 31.7%.

In contrast, the LCF is the fraction of the total building energy demand, which can be covered by the PV load. The LCF of variants 1 to 3 respectively amounts to 19.6%, 17.8%, and 17.1%.

The SPF rates the useful energy gain to the total energy input (electricity demand) of a HP. The highest SPF is achieved by variant 1 with 2.92. At 2.86, variant 2 (IWH) is comparable in efficiency as only heating is considered. Variant 3 has an SPF that is around 14% and 13% lower than the decentralized variants 1 and 2, respectively. It features an SPF of 2.50.

3.2. Economic assessment

The annuities presented in this section represent the costs per year distributed evenly over the observation period (20 years). Therefore, lower values are more advantageous. The annuities stated in this section merely represent the costs for installing the specific hydraulic variant described in section 2.2 and do not include any necessary retrofit of the building envelope. The annuities for all three variants are listed in Table 2.

The annuity of total annual payments (total annuity) of variant 1 (HIU) without PV system amounts to €116,390. In contrast, variant 2 (IWH) exhibits an 11% lower (€103,377) and variant 3 a 17% increased (€136,271) total annuity. The total annuity is composed of relatively high capital-related costs of €19,252, operation-related costs of €6,976 and demand-related costs of €90,162. Considering the installation of a PV system in variant 1 the total annuity is reduced by 17% to €97,145. The reduction is mainly caused by PV self-consumption, and thus, a decrease in demand-related costs of 19% to €72,718. PV-related proceeds of €5,644 further improve the economic analysis.

With total annuities of €86,672 (with PV) and €103,377 (w/o PV), variant 2 (IWH) is the most economical concept in this study. The demand-related costs at €81,410 (w/o PV) are the lowest of all three variants. The operation-related costs of €6,606 and the capital-related costs of €15,360 are relatively low and comparable to those of variant 3. The demand-related costs are lowered by 18% by considering a PV system and the PV-related proceeds accounts for €6,281.

The highest total annuity is achieved with €136,271 in variant 3. Although the capital-related (€16,776) and operation-related costs (€6,606) are comparatively low, variant 3 exhibits the highest demand-related costs (€112,407). The total annuity can be reduced by 15% to €115,779 by considering a PV system, due to lower demand-related costs (-17%) and PV-related proceeds (€5,327).

Table 2. Costs and annuities for the three hydraulic variants for DHW preparation with and without PV system.

Variant	Capital-related costs	Demand-related costs	Operation-related costs	Proceeds	Total annuity
#1 (HIU)	€19,252	€90,162	€6,976	-	€116,390
#2 (IWH)	€15,360	€81,410	€6,606	-	€103,377
#3 (centralized)	€16,776	€112,407	€7,088	-	€136,271
#1 (HIU) + PV	€22,472	€72,718	€7,599	€5,644	€97,145
#2 (IWH) + PV	€18,580	€67,143	€7,229	€6,281	€86,672
#3 (centralized) + PV	€19,996	€93,399	€7,711	€5,327	€115,779

3.3. Ecological assessment

For each component of each variant, the GWP was identified for the individual phases of its life cycle (cf. chapter 2.6.). Over a 20-year observation period, a total GWP of 1,580 tCO_2eq can be expected for variant 1. Thereof, 1,394 tCO_2eq are attributable to the actual operation phase of the variant, mainly due to the electrical power consumption of the HP and IWH. The share of all phases except the energy consumption amounts to 13% of the total GWP balance, and thus, are of minor significance. Mainly metallic materials are assigned a certain recycling potential after their service life. This is positively taken into account in the overall balance. Thus, a recycling potential of -22 tCO_2eq is considered.

Considering the WLCE of the three concepts, a clear distinction can be observed between centralized and decentralized solutions for DHW preparation, as can be seen in Fig. 6. Variants 1 and 2 exhibit similarly high values of 1,744 tCO_2eq and 1,746 tCO_2eq. Variant 3 features a WLCE that is approximately 34% higher than variant 1, with values of 2,341 tCO_2eq. Nevertheless, variant 1 (IWH) without considering a PV system exhibits the lowest WLCE.

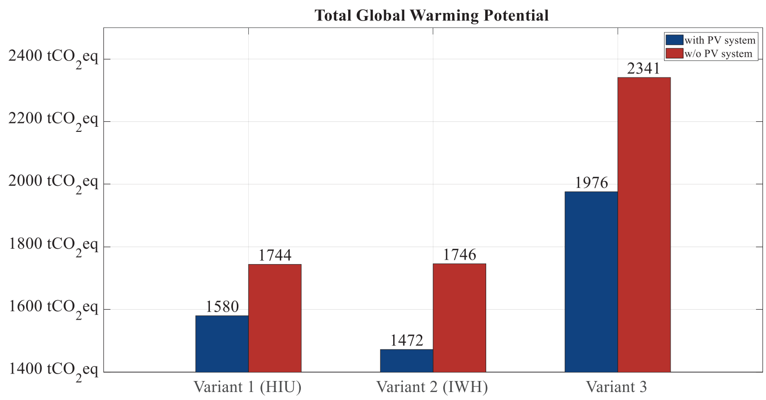

Figure 6. Total GWP in tCO_2eq for each considered DHW preparation concepts with and without PV system.

The installation of a PV system enables the use of PV surplus energy for the HPHS and additional energy-intensive components, like an IWH. In general, the PV self-consumption lowers the WLCE, due to reduced grid consumption. The WLCE is reduced by 9.4% (164 tCO_2eq) for variant 1 (HIU). Variants 2 and 3 exhibit a reduction in WLCE by installing a PV system of 15.7% and 15.6%, respectively. It is worth noting that variant 2 (IWH) performs significantly better than variant 1 (HIU) when considering PV systems, although similar WLCEs without a PV system. The WLCE is lowest in variant 2 (1472 tCO_2eq) when comparing the concepts with PV systems.

4. Discussion

4.1. Energetic, economic and ecological aspects

From an energetic perspective, the two decentralized variants offer clear advantages over the centralized variant for DHW preparation. However, the main reason for this can be attributed to the significantly different temperature regime in the TES, as the combined buffer storage tank in variant 3 must be heated to at least 60 °C for hygienic reasons. The average storage temperature was approximately 49 °C for variants 1 and 2 and 59 °C for variant 3. Accordingly, the temperature level at the condenser of the brine-to-water HP also differs by around 10 K. Although the heating output of the HP is reduced by only approximately 6% when the average condenser temperature rises, the electrical energy consumption increases by 18%.

The analysis reveals that the IWH (variant 2) is the most economical option both with and without PV. The combination of low demand-related, operation-related and capital-related costs are advantages for the use of a purely electrical DHW preparation. The highest capital-related costs of all concepts are the main drawback of an HIU, despite energetic advantages. Similarly, increased installation costs are expected, which could not be taken into account in this study. Especially in combination with a PV system, the low demand-related costs are remarkable, which could lead to HIU being considered as an economical alternative to pure electrical IWH. The decentralized concept (variant 3) offers a balanced cost structure but features the highest demand-related costs. The overall economic assessment of this option is therefore unfavourable.

The ecological assessment shows that the operated-related CO_2-equivalent emissions have the greatest impact (almost 90%) on the WLCE. The IWH (variant 2) with a PV system exhibits the lowest emissions and is therefore the most advantageous solution from an ecological point of view. The centralized concept (variant 3) performs worst ecologically due to its high WLCE. In general, installing a PV system offers advantages in terms of the economic efficiency and ecological efficiency of the HPHS. Although this measure does not reduce the final energy consumption, the use of self-generated electricity significantly reduces the amount of electricity purchased from the grid. All three variants perform significantly better if a PV system is added to the individual variants, than their respective versions without a PV system. Additional profits can be generated through feed-in tariffs or the sale of surplus electricity.

4.2. Recommendations for the implementation

A HIU (variant 1) is particularly advantageous in combination with a PV system, as high levels of LCF and SCF can be achieved. It is recommended for new buildings and complete retrofits with HPs and underfloor heating system, where low supply temperatures are possible and high system efficiencies can thus be achieved.

IWH (variant 2) is the most economical solution, as it offers both the lowest final energy consumption and the lowest investment costs. It is particularly well suited for buildings with low DHW demand per apartment or for retrofits with limited space.

Due to high thermal losses caused by distribution and circulation lines, a centralized DHW preparation (variant 3) is not recommended. The study highlighted that significant heat losses occur, particularly in centralized systems. Efficiency can be increased through optimized circulation control and optimized storage volumes. However, if an existing centralized system is to be replaced, the use of such a concept may be advisable for overall economic reasons.

Retrofitting existing buildings with decentralized solutions such as HIU or IWH and a combination of HPs, low flow temperatures, and optimized PV utilization is a sensible approach to achieving long-term economic and ecological benefits. In addition, the integration of smart control strategies can further increase system efficiency. Automated controls for TES loading in conjunction with PV generation could enable a higher degree of LCF and SCF.

4.3. Limitations

The test bench used for this study suffers from limitations that hinder an ideal comparison between the different hydraulic concepts. The two major limitations are listed below.

Compromises in the hydraulic design were particularly necessary for variant 3. The heat supply for SH is connected to the TES in a way that would not be implemented in a real system. Optimally, a combined buffer storage tank with additional connection flanges could be installed in order to separate the SH hydraulically from the heat supply provided by the HP.

The method used to extrapolate the measured values from the experimental runs to annual values could result in significant inaccuracies. Only two of ten reference days were used to evaluate the system. Although a winter reference day was selected which accounts for 50% of the days in the heating period, the system can lack dynamism due to higher or dynamic load profiles on the non-selected reference days. This could affect system efficiency and, if necessary, evaluate a variant positively or negatively in comparison to other concepts. However, this was not investigated as part of this study.

5. Conclusion

This paper investigates how different hydraulic concepts for DHW preparation affect the efficiency of a HPHS. Two decentralized concepts, one with a heat interface unit and one with an instantaneous water heater, and one centralized concept, with a combined buffer tank, are investigated.

The energetic assessment clearly shows significant differences between the concepts examined. Without a PV system, the HIU (variant 1) exhibits a higher final energy consumption than variant 2 with IWH. However, regarding the installation of a PV system, the HIU is more advantageous due to its higher LCF and SCF. The grid consumption is lowest for this concept. In contrast, the centralized variant with a constantly required 60 °C TES temperature and high circulation losses exhibits up to 38% higher final energy consumption.

The economic assessment indicates that the IWH (variant 2) is the most cost-effective based on its lower investment costs when calculated via the annuity method of depreciation. However, when PV integration is taken into account, the difference compared to the HIU (variant 1) is marginally. Thus, an HIU represents an attractive alternative, particularly in energy-efficient new buildings. A centralized DHW preparation (variant 3) features a up to 30% higher total annuity due to significantly increased demand-related costs.

The ecological assessment over the entire life cycle highlights the importance of a PV system. Both an IWH (variant 2) with PV and an HIU (variant 1) without PV have the lowest CO_2-equivalent emissions. With 34% higher CO_2-equivalent emissions, variant 3 shows the most negative results of all concepts considered.

In conclusion, the results show that the choice of the optimal system concept depends heavily on the building structure, domestic hot water usage, and economic conditions. While the IWH (variant 2) is the most cost-effective and efficient solution without PV, the HIU (variant 1) in combination with a PV system is the best choice in terms of energy and ecology. Centralized DHW preparation (variant 3) is only recommended in special cases, e.g., with constantly high DHW demand. Measures to reduce heat losses, as well as consistent use of low supply temperatures, contribute significantly to increasing the system's efficiency.

HIU are a suitable alternative to IWH in new builds and retrofits, particularly in apartment buildings. Their main drawback is the high capital-related cost, which may decrease with wider adoption. Overall, the two decentralized concepts are preferable to a centralized system for the DHW preparation.

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