Heat Pump Solutions in Renovations of Multi-Storey Buildings

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Abstract. EU set the target for deep renovation and for phasing out gas or oil-based heating systems to reach the ambitious climate goals. Although technical solutions for the renovation of multi-story residential buildings (i.e. window replacement, thermal insulation) and boiler replacement in central energy supply concepts already exist since several years, the renovation rate has been stagnating at a low level for years (well below 1% of the stock). This means that the ambitious climate protection goals in the building sector cannot be nearly achieved. Heat pump is a key technology also for building renovations to get rid of fossil fuel based technologies such as oil and gas boilers. In this study, a method is proposed targeting serial renovations of multi-apartment buildings. Simulations are performed deriving a guide to support decision-making considering both active and passive measures. Three energy renovation levels are applied in a building, located in Innsbruck, and several heating variants are implemented, which are categorised in central (one system per building), decentral (one system per apartment) and mixed. The calculated electricity consumption of the system to supply space heating and domestic hot water as well as the auxiliaries is used to rank the different solutions, resulting in a range between 19.7 kWh/(m^2 a) and 44.8 kWh/(m^2 a).

Keywords. Heat pumps, renovation, multi-storey buildings, thermal losses.
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1 Introduction

The European Union is aiming at reducing the CO$_2$ emission by at least 55% by 2030 in order to reach the goal of climate neutrality by 2050 [1]. To accomplish these ambitious targets, the national renovation rate has to be increased and financial strategies have to be developed to drastically reduce the energy demand. The building sector is responsible for 35% of the global final energy consumption, in particular, 22% is covered by the residential sector [1].

Within this framework, a research project explores innovative approaches for highly energy-efficient renovation strategies for apartment buildings in Austria, aiming to develop a new service model (one-stop-shop) for property managers, housing and owner associations through a targeted, novel mix of technical and non-technical measures. The technical measures are focused on modular and scalable building technology systems, multifunctional building components and standardization in industrial prefabrication that assure minimal disruption during the renovation process.

Due to the overall limited availability of renewable electricity and district heating on the Austrian level and the increasing demand, the thermal renovation of buildings is indispensable for achieving the climate goals. Switching from fossil heating systems to heat pumps is (often) only technically feasible in combination with an appropriate thermal renovation. To achieve a significantly higher renovation rate and phase-out of fossil-based heating systems, new minimal invasive and adaptive renovation processes are required, which merge construction and building systems with energy conversion based on renewable energy sources. Standardization and industrial prefabrication enable a reduction in costs and expenditure of time for the construction while the quality of the renovation is increased.

More than 250.000 combinations of building types were analyzed, ages, climate zones, building envelope efficiency levels and HVAC system configurations in Europe, also considering economic feasibility [2]. Besides, various renovation packages were also analyzed concerning their economic feasibility and environmental impact [3]. In Ref. [4], a comprehensive simulation study for a new housing development was carried out to develop a decision-making support tool regarding the choice of the heating system, the degree of centralization of the heating system, the heat distribution system and the corresponding degree of pipe insulation. In Ref. [5], guidelines for the deep renovation of buildings based on the experience with demo buildings are provided.

This contribution highlights the potential of serial renovations with different heat pump solutions. These solutions are categorised in central (one system per building), decentral (flat-wise) or mixed heating systems, aiming to be the basis for serial, adaptive and industrialized renovations with heat pump solutions. In a reference multi-story building, these solutions are investigated through simulations calculating the final electricity i.e. the electricity consumption to supply space heating, domestic hot water (DHW) and auxiliaries.

2 Methodology

2.1 Proposed method

This work aim at proposing a methodology tailored to support the planner to select the most suitable solution for each specific renovation case study. A simplified scheme of the proposed method can be seen in **Fig. 1**. The first step of this scheme, which supports the whole process, is the collection of all the relevant information. A checklist of required inputs regarding both technical and non-technical aspects is provided. In the second step, the collected data are used to select a bundle of possible solutions regarding the envelope and the system with the help of the decision tree developed within the research project. The set of solutions are then analysed within an iterative process in which the generation, distribution and emission systems have to be sized and the minimum requirements for the envelope quality have to be assessed excluding unfeasible solutions (e.g. compact heat pump system with air heating in combination with a non-insulated envelope have to be excluded). The number of feasible solutions, as an outcome of this step, should be reduced and for the remaining solutions, a calculation of the energy balance is performed considering the integration of renewables. At this point, it is possible to evaluate the life cycle cost and investment cost of each selected combination and from here based on technical and non-technical aspects, the "best" solution can be selected.

This simulation study focuses mainly on step 2, aiming to set a basis to support decision-making. In step 1, after the collection of the required data for the building, some decisions were made such us that new radiators have to be installed. The simulation results for step 2 include three renovation levels from the building envelope point of view, and several variants of centralised, decentralised of mixed heating systems. Finally, the required electricity for various distribution and emission systems combined with heat pumps is calculated.

The used simulation model is based on Matlab using the Carnot toolbox presented in [4].

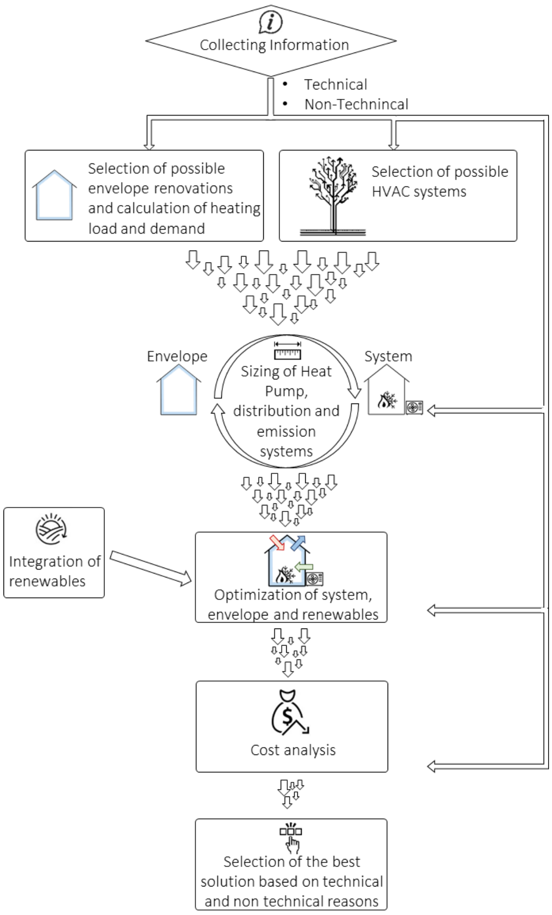


Fig. 1 – Scheme of the proposed method

2.2 Building and climate

The modelled building that is located in Innsbruck and a floor plan including the four flats are shown **Fig. 2**.

Fig. 2 – Outside view of the multi-family building and a floor plan (NHT, Innsbruck).

The main characteristics of the building are summarised in **Tab. 1**.

Tab. 1 - Building characteristics.

Description	Quantity
Treated area [m²]	1296
Foot print area [m²]	449
Storeys	4
Flats per storey	4
Area of the flats [m²]	73/98/98/109
Persons per flat	3

Innsbruck has relative cold winters and mild summers. Thus, cooling demand is almost negligible at the moment, however, is increasing over the years due to comfort reasons. The related climate data of i.e. monthly global radiation and ambient temperature are depicted in **Fig. 3**.

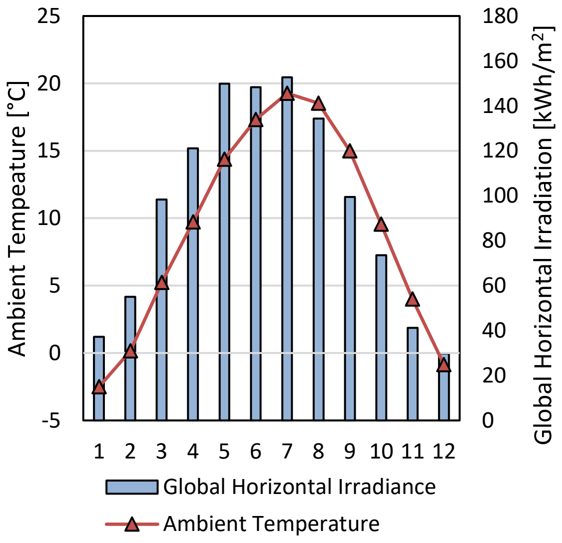


Fig. 3 – Monthly global radiation and outside temperature in Innsbruck

Three renovation levels are applied to the building, as shown in **Tab. 2**, which summarizes the corresponding requirements for space heating and domestic hot water. The HD25 is based on EnerPHit standard [6], the HD45 is similar to EnerPHit but the mechanical ventilation is without heat recovery, and the HD60 is based on the Austrian standards [7].

Tab. 2 – The space heating and DHW demand for the three renovation levels.

	HD25	HD45	HD60
Space heating [kWh/(m²a)]	25	45	60
Building energy Standards	EnerPHit [6]	EnerPHit without heat recovery [6]	Austrian standards [7]
DHW [kWh/(m²a)]		19.8	

Remark: mechanical ventilation with heat recovery is considered in HD25 and not in HD45 and HD60

2.3 Heat pump, distribution and emission systems

A selection of central, decentral and mixed hydraulic solutions is analysed and compared in order to evaluate the influence of heat pump performance, distribution losses and auxiliary energy on the final energy consumption of the systems. The overall efficiency depends in particular on the temperature level of the system: On the one hand, the heat losses increase with a higher temperature level, on the other hand, especially in heat pump systems, the temperature level has a major influence on the efficiency of heat generation.

Air-source heat pumps are used with COP of 3.7 at 2 °C outdoor temperature and 35 °C flow temperature and COP of 2.4 at 7 °C outdoor temperature and 55 °C flow temperature. The flow temperature is varied within the heating period based on the ambient temperature i.e. a so-called heating curve is implemented. In simulations, the COP is calculated dynamically for the given source and sink temperature. The investigated emission systems are mainly radiators or air heating in case of deep energy renovation i.e. low space heating demand.

In order to achieve the goal of a minimally invasive renovation, several different heat pump solutions are analysed:

1. Central solution: A central heat pump should supply the entire building with both space heating and domestic hot water. To guarantee a minimally invasive renovation, the distribution can take place via the old central distribution system or, if this can no longer be used, by laying cables in the staircase or in the facade.

2. With the mixed solution, decentralized systems are used for the preparation of domestic hot water, while

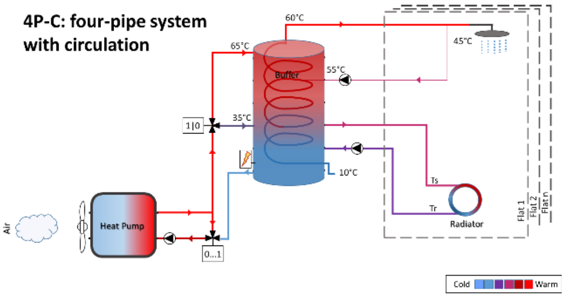
a central heat pump provides the space heating, which can be significantly smaller than the heat pump of the previous category.

3. In the case of decentralized solutions, both the DHW preparation and the space heating of each flat is prepared individually. This solution can be implemented with various technologies such as compact heat pumps or separate components for hot water preparation, heating and ventilation.

The modelled systems are presented in **Tab. 3**. Additionally, the hydraulic scheme of each system is presented in **Fig. 4** for central ones, in **Fig. 5** for mixed ones and in **Fig. 6** for decentral ones.

Tab. 3 – Investigated systems-variants

	Description	Abbreviation
Centralised	four-pipe system with circulation	4P-C
	four-pipe system with fresh water station	4P-FWS
	two-pipe system with fresh water station	2P-FWS
Mixed	two-pipe system with charging window	2P-CW
	two-pipe system with e-boilers	2P-EB
	two-pipe system with e-boilers and shower-drain water heat recovery	2P-EB&DWHR
	two-pipe system with DHW heat pumps	2P-DHW_HP
Decentralised	split units and e-boilers	SU&EB
	split units and DHW heat pumps	SU&DHW_HP



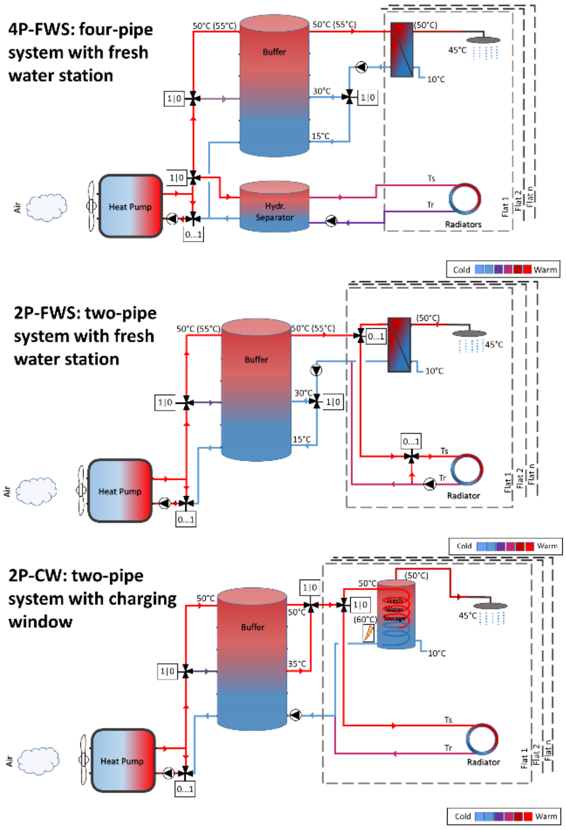


Fig. 4 – Hydraulic schemes of the variants with centralised solutions

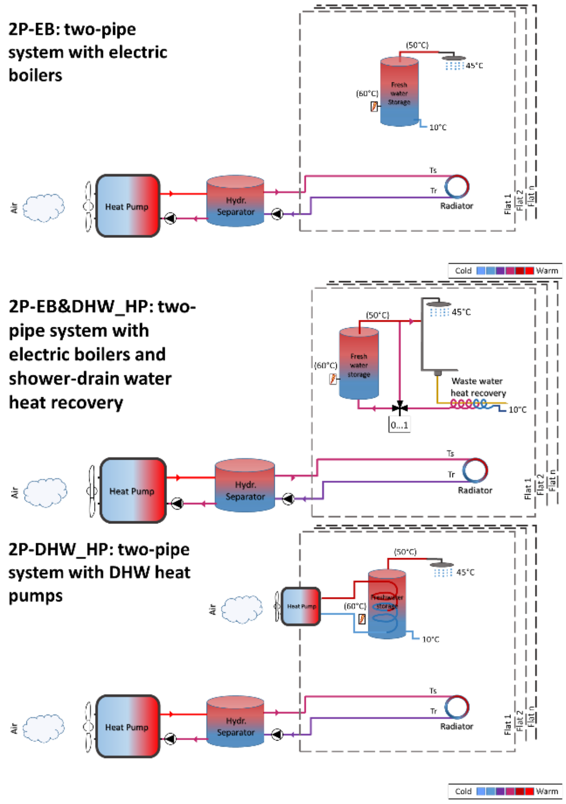


Fig. 5 – Hydraulic schemes of the variants with mixed solutions i.e., centralised for SH and decentralised for DHW

The pipe-distribution systems are designed according to Austrian/European standards [8,9], and the size of the pipes vary based on the heating demand levels and the corresponding flow and return temperature (see **Tab. 4**).

Tab. 4 – Flow and return temperature for space heating (SH), and .DHW temperature based on three renovation levels

	HD25	HD45	HD60
Flow temperature for SH [°C]	40	45	55
Return temperature for SH [°C]	30	35	40
DHW temperature [°C]	55 (except:2P- or 4P-FWS with 50 °C and 4P-C with 60 °C)		

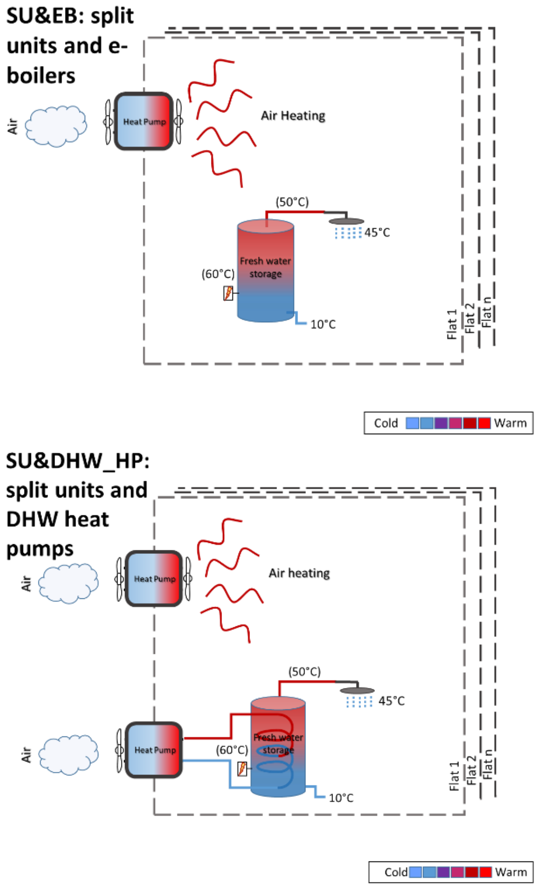


Fig. 6 – Hydraulic schemes of the variants with decentralised solutions

3 Results and discussion

Fig. 8 presents the electricity consumption of all the simulated systems in the three renovation levels. These results can be used to support decision-making process finding the optimum combination of envelope quality and HVAC system configuration. For example, it can be observed that electric boilers should be avoided since even in HD25 with low space heating demand the systems with electric boilers require more electricity than the other systems in HD45 or similar level to other systems in HD60. The installation of shower-drain water heat recovery combined with an electric boiler reduces the consumption significantly by 4.5 kWh/(m² a), however, it is not enough to change the order in the ranking of the systems. It must be noted that the required thermal comfort level is reached in all variants.

Comparing the different solutions in each renovation level, the central system 4P-FWS is the optimal one with the lowest electricity consumption in all renovation levels. In HD25, the mixed system 2P-DHW_HP, and the decentral system SU&DHW_HP result in similar electricity consumption. The central systems 2P-FWS and 2P-CW have slightly higher consumption compared to 4P-FWS. In addition, the later has the advantage that it can also supply cooling compared to other 2-pipe central systems that cannot.

4P-C in HD25 consumes more than other systems in HD45 such as 4P-FWS and 2P-DHW_HP, therefore, it cannot be suggested.

Fig. 7 presents the electricity consumption of the investigated systems for the HD25, which is separated in the electricity dedicated to space heating, DHW and auxiliaries. As can be seen, the requirement for space heating does not vary significantly between the different systems mainly due to high heat pump performance because of low flow temperature. However, the requirement for DHW varies significantly between the systems. For example, the consumption in case of DHW_HP is 9.6 kWh/(m² a) and in case of 4P-C is 14.4 kWh/(m² a). The reasons for that differences are the choice of a heat pump or an electric boiler, the use of central or decentral DHW system (with or without distribution losses), and the different required DHW temperature (**Tab. 4**) that influences significantly the performance of the heat pump and the distribution losses.

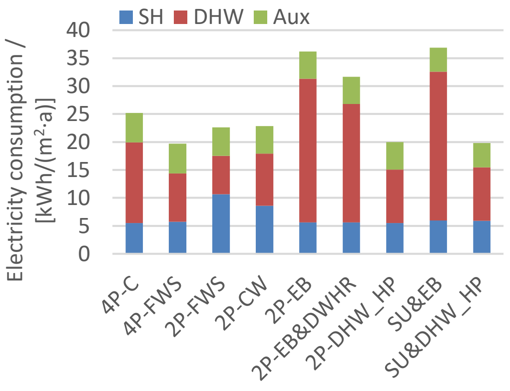


Fig. 7 – Required electricity for SH, DHW and Aux for the different variants applied in renovation level HD25. Remark: distribution losses in 2P-FWS and 2P-CW are dedicated in SH, however, are for both SH and DHW.

In **Fig. 9**, the overview of the energy flows for the central 4P-FWS system are shown in a Sankey diagram. The distribution losses are 7.8 kWh/(m^2 a) from which the 2.6 kWh/(m^2 a) can be used as gains in heating period. In addition, the mechanical ventilation with heat recovery reduces the heating demand by 15 kWh/(m^2 a). In such a renovation level, the demand of DHW and space heating are in the similar range.

As mentioned in the proposed method, the final choice of the system depends on the challenges and the costs for implementing these measures. Usually, when a central system can be an option is less expensive than the use of decentral ones. However, often that is difficult to realise. Besides, space limits and sound emissions should be considered in the decision-making process.

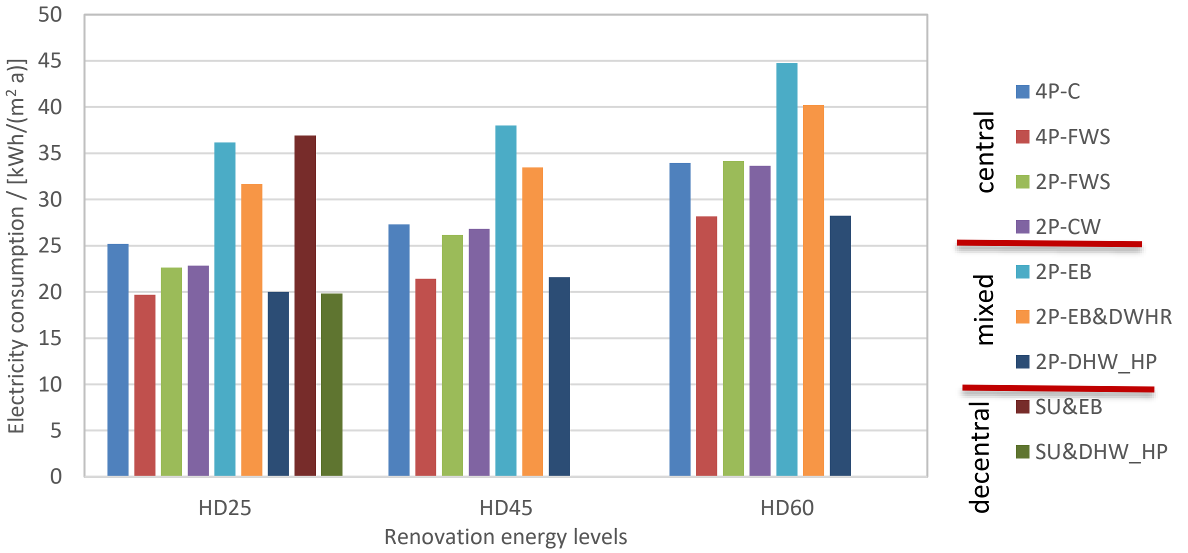


Fig. 8 – Final energy (electricity) required by the heat pump and auxiliaries (including mechanical ventilation) in the three renovation levels (25, 45 or 60 kWh / (m2 a)). Remark: Decentralized systems not simulated for HD45 and HD60 (not recommended).

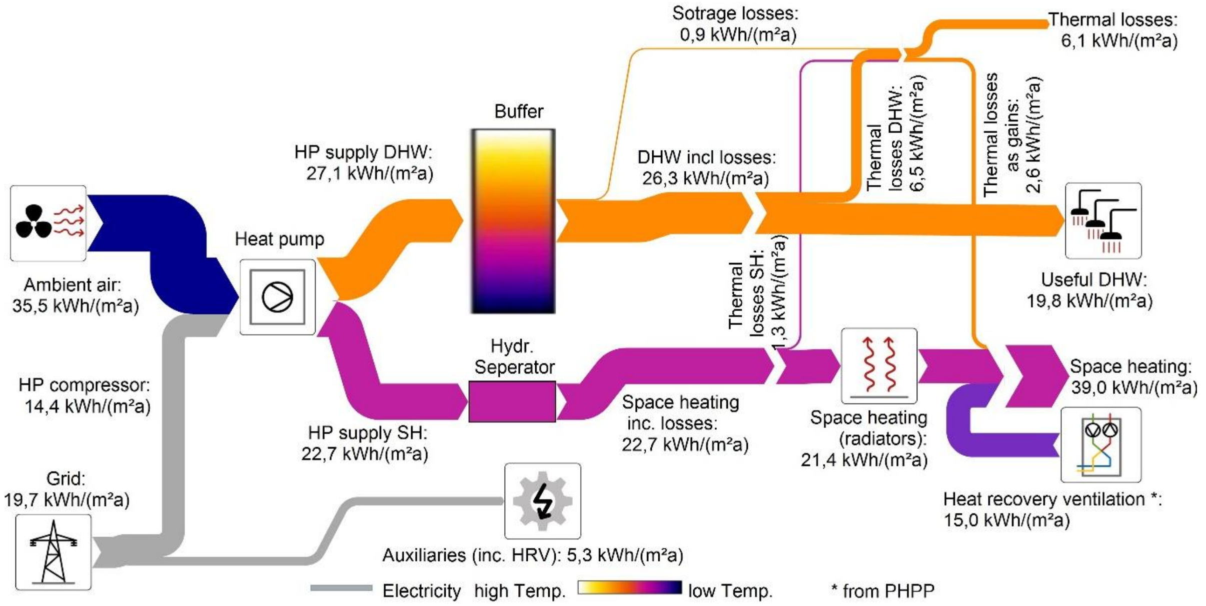


Fig. 9 – Sankey diagram of the centralised 4-pipe distribution system with fresh water station (4P-FWS) implemented in renovation level HD25 (i.e. 25 kWh/(m^2 a))

4 Conclusions

A method is proposed targeting serial renovations for multi-apartment buildings. Aiming to support decision-making, simulations are performed considering three renovation levels from the thermal envelope point of view and several heat production, heat distribution and emission systems categorised in central (one prebuilding), decentral (one per flat) or mixed solutions.

The electricity consumption for the different solution varies significantly from 19.7 kWh/(m^2 a) up to 44.8 kWh/(m^2 a). The energy optimal solutions in each renovation level (thermal envelope), are the central system 4P-FWS and the mixed one 2P-DHW_HP. In addition, the decentral SU&DHW_HP has similar performance, however, it is suggested to be used in HD25 with low heating load in which air heating can be an option due to comfort reasons. Besides, the central 2P-FWS and 2P-CW have slightly higher consumption than the optimal systems in HD25, thus, the decision can be made considering also other criteria such as non-technical or economic ones.

The not recommendable solutions from the energy point of view are those with circulation for DHW (4L-C) and those with electric boilers, even if deep renovation is applied.

Finally, the final decision depends on a combination of energetic and economic evaluation, and non-technical criteria such as resilience, possibility of cooling, space issues, etc. In a future work, economic calculations including investment, operation and maintenance costs should be performed.

5 Acknowledgement

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