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DECARBONISATION THROUGH INNOVATION

Simulation-based heat pump system design and optimization for multi-apartment buildings

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Abstract

The progress of the energy transition in the building sector remains insufficient, particularly for existing multi-apartment buildings where the replacement of fossil-based heating systems with renewable alternatives such as heat pumps (HP) is still limited. Besides financial barriers and the owner - tenant dilemma, several technical challenges hinder widespread adoption. These include ensuring appropriate system sizing, maintaining acceptable flow temperatures for efficiency, and mitigating noise issues - all within the spatial constraints typical of existing buildings. To address these complexities, software-based integrated planning methods are essential to ensure reliable and efficient system design. In the early project stages, spreadsheet-based tools (e.g., PHPP) are widely used by practitioners for pre-design and proof-of-concept studies. However, the detailed design and techno-economic optimization of HP retrofits require higher temporal resolution and more sophisticated dynamic simulation tools. Therefore, a modular toolbox is proposed to enable a consistent workflow - from pre-design to detailed design and optimization - allowing seamless transition from spreadsheet tools to dynamic simulation environments. The toolbox supports variant management, integrated post-processing, and transparent visualization of energy fluxes and optimization potentials. The methodology is demonstrated through a renovation case study of a multi-apartment building in Vienna, Austria. Several renovation levels and heat pump concepts (heat source, system configuration, and heat emission system) are analyzed and compared in terms of energy and economic performance. The proposed workflow provides a scalable and knowledge-based planning method to support heat pump implementation in multi-apartment building renovations, accelerating the transition towards a renewable and efficient building stock.

Keywords: techno-economic optimization; heat pump system, building and HVAC simulation; energy transition; workflow

1. Introduction

Heat pumps (HPs) have gained increasing importance in recent years and are now widely integrated into flats, multi-apartment buildings (MAB), building blocks, and district-level energy systems such as district heating networks [1]. The rising number of studies on HP applications in MAB reflects this trend, yet practical experience and field data—particularly for existing and thermally renovated buildings—remain limited. Planning HP systems for MAB is inherently complex due to the wide range of design options, heat sources, control strategies, and integration pathways, making simulation-based approaches highly recommended for efficient and reliable system design [2]. Recent studies have investigated the performance of HP systems in MAB from various angles: the influence of operating and return temperatures on system performance [3] and [4], improvements in domestic hot water (DHW) preparation [5], component selection and integration aspects [6], and potentials and constraints of different heat sources [7]. Hybrid configurations combining district heating and local HPs have also been addressed, including market-based control strategies [8], high-temperature HP concepts [9], and TRNSYS-based modelling of hybrid district–local HP systems [10]. The impact of renovation level on flow temperature, HP sizing, and system performance has further highlighted the need for integrated planning [11] and a holistic approach to thermal renovation planning with HP integration in MAB was presented in [12].

Despite these advances in HP systems in MAB, a systematic understanding about an integrated design process including renovation measures and HP system design in MAB is still missing. In particular optimization on HP system level has not been addressed in previous works, which is required to ensure long-term performance. In this contribution, the suggested workflow is tested using a simulation-based approach on a case study MAB with six flats on three stories to identify cost-optimal solutions.

2. Method

2.1. Test Case

The test case is a real building, a point block development in Vienna with 6 flats on 3 floors and with a treated floor area of 365 m², see Fig. 1. The building was built in 1963 and partly renovated in 1990. Tab. 1 summarizes characteristic data of the building. The relatively small flats are heated with individual flow-type gas boilers that are either installed in the bathroom or the corridor. It is assumed that radiators with a flow temperature of 65 °C have been installed when the building was partly renovated in 1990.

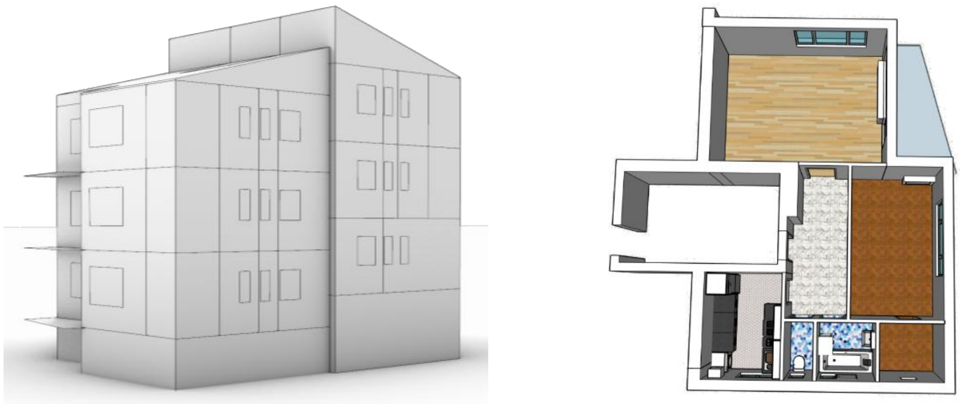

Figure 1. Test Case Building with 6 flats on 3 stories, left: 3D visualization, right: floor plan

Table 1. Characteristic data of the test case (1963 original building, 1990 status quo, pre-renovated).

HP	1963		1990
Area (GFA) – EPC / [m_{GFA}^2]		455	
Area (TFA) – PHPP / [m_{TFA}^2]		365	
Heating Demand / [kWh/(m_{TFA}^2 a)]	247		134
DHW Demand / [kWh/(m_{TFA}^2 a)]		13.7	
Heating Load / [W/m_{TFA}^2]	87		51
Number of persons		10	

For domestic hot water standard tapping profiles are used (EN 16147 'M', see Fig. 2) and scaled depending on the number of persons (4, 2.5 and 1.65). The simultaneity factor is calculated to φ_{VDI} = 0.31 following the guideline VDI 2072 for n_{flat} = 6. The tapping profiles are shifted accordingly see Fig. 2 resulting in a simultaneity of φ = 0.35. The hourly average underestimates the peak power and is only used for the energetic calculation.

$$\varphi_{VDI} = 0.03 + 0.5 \cdot n_{flat}^{-0.5} + \frac{0.47}{n_{flat}} \quad (1)$$

It is important to remark that the number of persons has direct influence on the DHW energy demand but does not influence the peak power and thus not the required capacity and dimensions of the equipment. In the following an average of 9.9 person per building is assumed which corresponds to a common assumption of 30 m²/person.

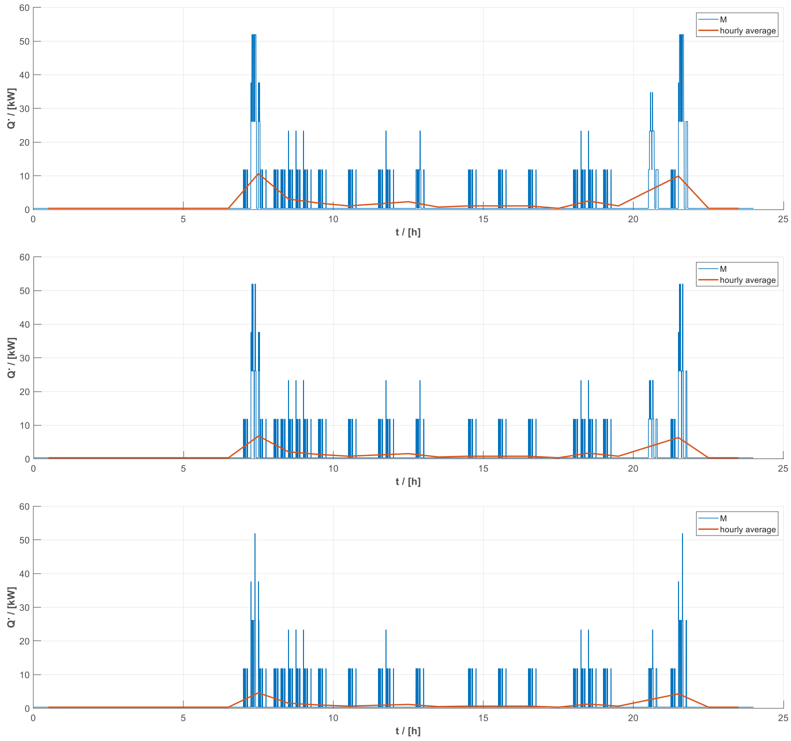

Figure 2. Tapping profile based on EN 16147 'M' for 6 flats with 4 (top), 2.5 (center) and 1.65 (bottom) persons/flat in average and a simultaneity of 0.35.

DHW Preparation in MAB

For MAB there are several different HP system concepts available. The most common are systems with a central HP for SH and DHW preparation and mixed systems, i.e. central SH HP and decentral E-boiler or FTPH for DHW preparation. Fully decentral variants exist, too, but are rather exceptions and not further considered here. Semi-central system solutions with a central low/medium temperature HP and decentral booster HPs can have advantages in terms of performance, but are challenging from the economic point of view. The most common HP system concepts are listed with the typical flow and return temperature for DHW.

- 4 pipe circulation (4p C): 60/55
- 2 pipe heat transfer station (2p HTS): 55/30
- 2+2 pipe fresh water station (2+2p FWS): 55/30
- 2 pipe decentral buffer (2p buffer): 55/30 (in so-called charging windows of e.g. 3 x 2 h)
- 2 pipe E-boiler (2p EB): 60/-
- 2 pipe flow type post-heater (2p FTPH): 45/-
- 2 pipe decentral DHW-HP (2p DHW-HP): 60/-
- 2 pipe DHW booster (2p DHW-B): 35/30 (in case of FH)
- 2 pipe SH+DHW booster (2p B): 20/15 (as an example)

Detailed dynamic building and HVAC simulation results for the systems 4pC, 2+2p FWS, 2p B and 2p EB with air/water-HP and for the case of existing radiators can be found in [13].

2.2. Integral Planning and Method

The aim of the integral planning process is to find the global energetic and economic optimum with regard to the thermal renovation and the HP system, taking into account the boundary conditions (i.e. climate) and constraints (i.e. space availability, restriction of heat pump size due to noise emissions and refrigerant quantity, economic restrictions) of the project. The optimal solution for renovation and heating system replacement depends on the specific project goal and can vary depending on the specifications and constraints. Typically, optimization is either based on maximum efficiency or minimal CO_2 emissions at a given maximum cost, or on minimal costs at a given efficiency or CO_2 emissions target. In relation to the entire solution space, there

are suboptimal solutions that are not considered further and those known as Pareto-optimal solutions. Selecting a solution from the Pareto front then requires individual weighting.
In this contribution, different “renovation packages” are compared:

- three thermal renovations (none, standard renovation: BAU, deep renovation: BEST),
- two variants of heat emissions systems (existing, new),
- four heat pump system variants (4p C, 2+2p FWS, 2p HTS and 2p EB) and
- 2 HP heat sources: air/water (A/W)-HP , brine/water (B/W)-HP

Out of 48 possible combinations only the relevant ones are compared, i.e. the case of the existing building with existing radiators and A/W-HP is considered infeasible. Furthermore, new radiators are only considered if these result in a reduced flow temperature. More details on the integral planning workflow can be found in [12] and [14].

2.3. Model

The building thermal envelope is pre-designed using a spreadsheet approach (monthly energy balance, PHPP). Different thermal envelope qualities are considered from existing to very efficient renovation, considering both partial renovations (e.g. roof or windows only) and different energy efficiency targets, e.g. standard renovation acc. to OIB:2023 (https://www.oib.or.at/) referred to as BAU, or deep renovation acc. to EnerPHit standard (passiv.de) referred to as BEST. Based on these renovation levels, heating demand and heat load are determined using a dynamic 1-zone thermal model. The thermal load curve is post-processed with an hourly time step. Based on the floor plan and the renovation level, the critical room is identified and based on the available information about the existing radiators or the assumption of new radiators (type, size) the required flow temperature is determined. The radiator equation is used to determine the required flow temperature using a radiator exponent of n = 1.4.

$$\dot{Q} = \dot{Q}_{nom} \cdot \left(\frac{\Delta T_{log}}{\Delta T_{log,nom}}\right)^{n} \quad (4)$$

Using heating (max daily) the load the heat pump capacity and storage volume is determined. A generic performance map for the coefficient of performance (COP) is considered for a A/W HP or a B/W HP as in Tab. 2.

Table 2. Generic Performance Map of the COP of an air/water HP and a brine/water HP

HP	A/W	B/W
A-2W35	2.9	4.1
A-2W55	1.9	2.4
A7/W35	3.7	5.1
A7/W55	2.3	3.0

The heating capacity of the A/W HP increases with ca. 2.5 % per K and the B/W HP with 2 % per K related to the source temperature. The influence of the sink temperature on the heating capacity is almost negligible: In case of A/W HP a reduction of the heating power by ca. 7 W/K is considered; the capacity of the B/W HP is assumed to be independent of the sink temperature. The HP is modelled with an average Carnot Performance factor of $\eta_C = 0.34$ for A/W HP and $\eta_C = 0.47$ for B/W HP and the Carnot COP based on the system (T_{max}) and source (T_{min}) temperatures.

$$COP = \eta_c \cdot \frac{T_{max}}{T_{max} - T_{min}} \quad (5)$$

For the brine/water HP a constant source temperature of 10 °C is assumed which is an optimistic assumption and considers that the borehole heat exchanger (BHX) is well dimensioned and regenerated in summer.

The pipe lengths and diameters are calculated based on the HP system (see section 2.2) the number of rising ducts (here 1). For the pipe insulation (DN100), the storage quality (ErP B), set points (20 °C), etc. default values are assumed and can be varied in a parametric analysis. In [14] more details on the used model can be found. The results of the simplified model used in this work have been compared against the detailed simulation results that can be found in [13].

2.4. CO_2 Emissions and Reference

It is assumed that in the existing building, both the SH and DHW are supplied by a flat-wise gas-fired flow-type gas heater with a system efficiency of 85%. The reference case results in a total heat energy demand of 209 kWh/(m^2_{AT}a) and CO_2 emissions of 43.5 kgCO_2/(m^2_{AT}a) using the conversion factor of 201 gCO_2/kWh) acc. to OIB6:2023 (https://www.oib.or.at/).

2.5. Cost Functions

Cost functions are implemented for components of the thermal renovation as well as for the components of the HP system. Annual costs are calculated considering the service life of the components and an interest rate of r = 3 % based on the annuity AIC (eq. 2) with the initial costs (IC) and the service life N of the components. Details about the cost-functions can be found in [14]. Considering a gas price of 0.1 EUR/kWh, the annual operating and maintenance costs amount to 23.7 EUR/(m^2_{AT} a) for the reference case. Average electricity costs of 0.31 EUR/kWh are assumed. Total annual costs (TAC) include annual maintenance costs (MC) and operation costs (OC) (i.e. gas and/or electricity):

$$AIC = \frac{IC \cdot r}{1-(1+r)^{-N}} \tag{2}$$

$$TAC = AIC + OC + MC \tag{3}$$

Tab. 3 summarizes the cost functions for the HVAC components. It is important to remark that in particular the assumptions for the maintenance for the decentral fresh water station (FWS) for the 2+2-pipe system and for the decentral heat transfer station (HTS) for the 2-pipe system as well as for the decentral E-boiler are rather optimistic. Furthermore, the initial costs for the borehole heat exchanger (BHX) are also rather on the lower side. Overall, all assumptions for the cost strongly depend on the region and are subject to change and need to be individually checked and in case adapted.

Table 3. Cost functions for the HVAC components [14]

Component	Initial	Maintenance	Service Life / [a]
Radiator	80 €/m^2_{AT}	0	30
Buffer store	20.5 €/l	0.5€/l/a	30
A/W HP	4310*P[kW_{th}]$^{0.6177}$ €	14 €/kW	15
B/W HP	1948.2*P[kW_{th}]$^{1.0138}$ €	14 €/kW	15
BHX	1000+1667 €/kW_{th}	0	40
Pipe	1.22 €/m/mm	0	30
Pipe insulation	1.06 €/m/mm	0	30
Pump	0.41 €/l/S	0.006€/l/S/a	15
FWS (decentral)	3250 €/System	0	30
HTS (decentral)	3500 €/System	0	30
Central FWS	10000 €/System	0	30
E-boiler	1100 €/System	0	30

2.6. KPIs

The renovation packages are compared in a techno-economic study in terms of reduction of CO_2 emissions (ΔCO_2) and in difference of invest (EUR) and life cycle costs (total annual costs TAC, EUR/a) with respect to the reference case. In addition, the required flow temperature (FT) and the required HP capacity as well as the seasonal performance factor, which includes the electricity demand of the heat pump and all auxiliary energies (AUX) are evaluated.

$$SPF_{sys} = \frac{Q_{DHW}+Q_{SH}}{W_{HP}+W_{AUX}} \quad (6)$$

3. Results

The heating demand (HD) and heating load (HL) are shown in Fig. 3 for 12 different cases (from existing building) to EnerPHit renovation (BEST), for both simulation and PHPP. The agreement is good, while PHPP underestimates the heating load for the poor envelope qualities and slightly overestimates for the cases with low heating demand. The HD can be reduced from ca. 135 kWh/(m² a) to ca. 25 kWh/(m² a). The HL reduces from ca. 55 W/m² to ca. 18 W/m². A flow temperature of 50 °C (as an example) requires a HL of ca. 32 W/m² or less i.e. a thermal renovation to ca. 68 kWh/(m² a) (acc. to PHPP).

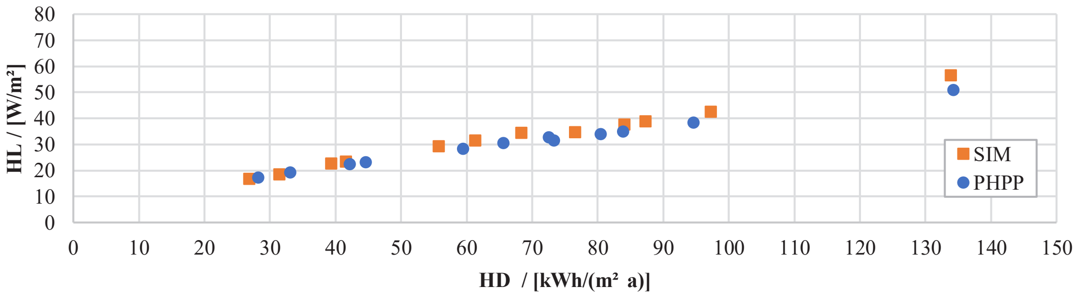

Figure 3. Heating load (HL) (max daily) vs. heating demand (HD) for the existing building (pre-renovated) 12 different renovation steps (20 °C SP)

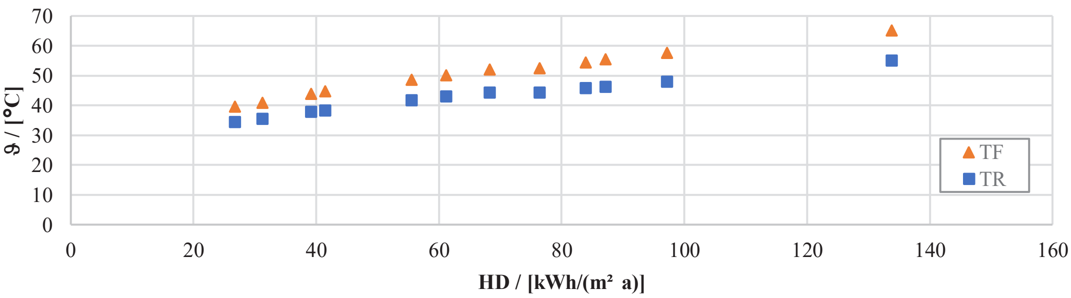

Figure 4. Required flow and return temperature depending on the level of HD assuming the existing type 21 plate radiators (20 °C SP)

It is noteworthy that the heat load calculation according to EN 12831-1 delivers (even disregarding reheating) significantly higher HL: ca. 30 % for the existing 50 % for the renovated and even 90 % for the deep renovated building, see also [11]. In order to avoid oversizing, it is recommended to use the max. daily HL from dynamic simulations, but it is important to note that there is ongoing discussions with respect to the compliance with the standards. For the case with DHW three charging windows of each 2 h are assumed, which leads to an increase of the required HP capacity by 24/(24-6) = 1.33.

Exemplarily, HPs of the series ALM (iDM, Austria) are selected for three different cases based on the simulated HL and summarized in Tab. 4. These four HPs are all Monoblock A/W-HP with natural refrigerant (R290) and all have variable speed control, the ALM MAX 10-50 has two separate refrigerant cycles. These HPs cover a heating capacity under nominal conditions of 8 kW (ALM 2-8), 12 KW (ALM4-12), 15 kW (ALM 6-15), 24 KW (ALM 10-24) and 50 KW (ALM MAX 10-50), see https://www.produktdatenbank-get.at or https://www.idm-energie.at/ for more technical details. Sizing is performance for a bivalence point at -2 °C.

Heat pump capacity and thus size reduces significantly with the better thermal envelope. Finding space for the installation of a large capacity HP might be a challenge in many locations, also considering the higher sound pressure level which requires a larger distance to the neighbors, see also Fig.9, below.

Table 4. Heating load (HL), HP capacity, HP type and size and sound emissions (sound power level) for three selected building qualities; bivalence at -2 °C; *) Sound power level acc. to https://www.produktdatenbank-get.at and data sheet (iDM); **) instead of one ALM 10-24 also two ALM 6-15 are possible; ***) instead of one ALM 4-12 also two ALM 2-8 are possible.

	None	BAU	BEST
HD / [kWh/(m² a)]	133.8	68.3	26.7
HL (HP Capacity w/o DHW) / [kW]	18.6	12.7	6.2
HP Capacity w/ DHW / [kW]	24.8	16.8	8.2
HP Type w/o (HP Type w/ DHW)	ALM 10-24 (ALM MAX 10-50)	ALM 6-15 (ALM 10-24)**)	ALM 2-8 (ALM 4-12) ***)
HP Size w/o (w/ DHW) / [mm]	1461x1928x997 (1514x3748x1005)	1432x1575x795 (1461x1928x997)	960x1600x800 (960x1600x800)
Sound Pressure Level (nom/max)*) (w/ DHW) / [dB(A)]	50/55 (57/NA)	50/55 (50/55)	45/55 (51/57)

Fig. 5 shows the electricity demand for the different renovation levels and HP system concepts. The difference in IC and CO_2-emissions with respect to the reference case is shown in Fig. 6 while Fig. 7 shows the difference of the projected annual investment costs (AIC) and Fig. 8 the difference of the total annual costs.

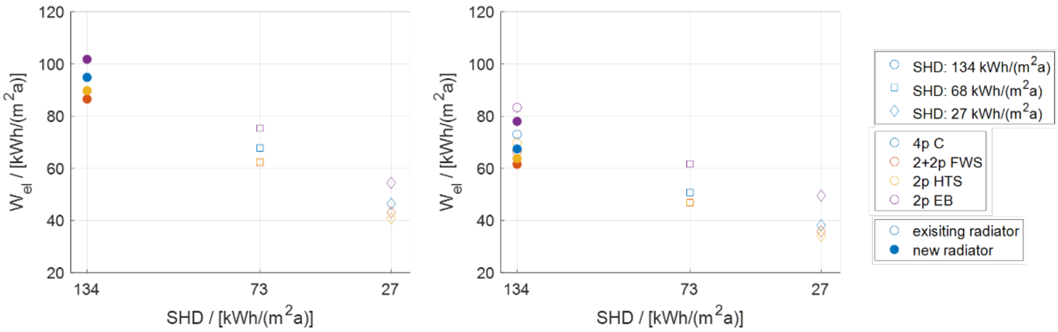

Figure 5. Electricity demand for the different renovation levels and HP system concepts (left) A/W-HP (right) B/W HP. (none: 134 kWh/(m² a), BAU: 73 kWh/(m² a), BEST: 27 kWh/(m² a)).

The electricity demand ranges from ca. w_{el} = 105 kWh/(m² a) for the non-renovated building with A/W-HP and E-boiler to below 40 kWh/(m² a) for the deep renovated building (BEST). In the very best case, the BEST building with B/W-HP with 2p HTS or 2+2p FWS, the difference between the HP systems is small and within the uncertainty and the ranking does change between the renovation and radiator cases. Overall, the influence of the renovation level is more significant than the choice of the HP-system, but within one renovation level, the difference between the best and the worst HP system is still relevant with a difference between around 15 kWh(m² a) and slightly higher than 20 kWh(m² a). It is remarkable that cooling would not be possible with the 2p HTS system.

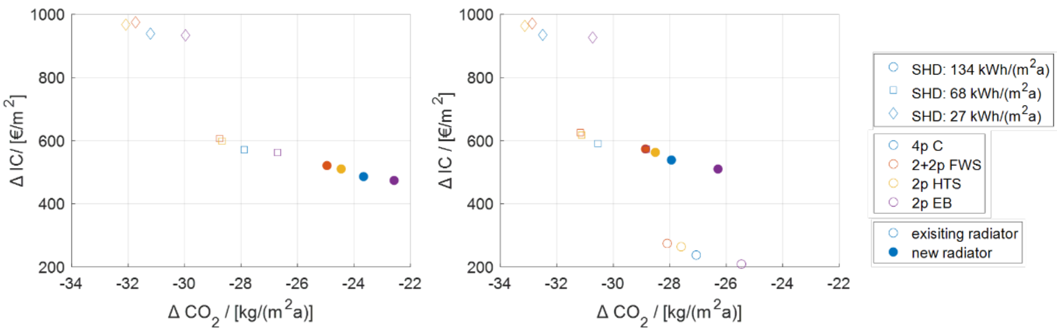

Figure 6. Difference between investment costs (IC) and CO_2-emissions compared to the reference case (new flow-type gas boiler, non-renovated case), based on Fig. 5.

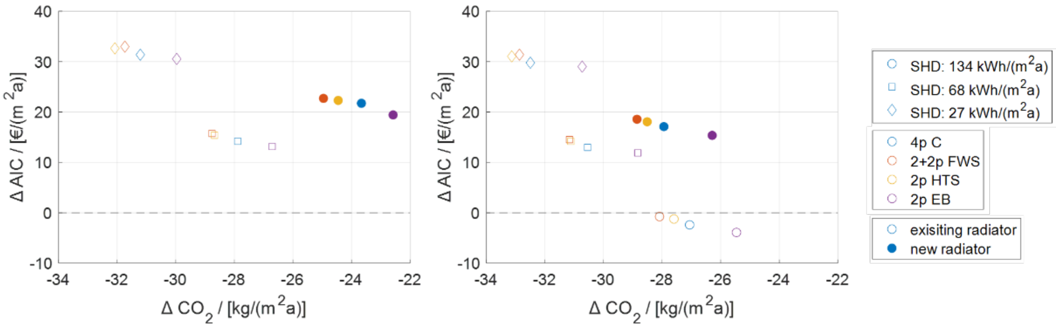

Figure 7. Difference between projected annual investment costs (AIC) and CO_2-emissions compared to the reference case (new flow-type gas boiler, non-renovated case), based on Fig. 5.

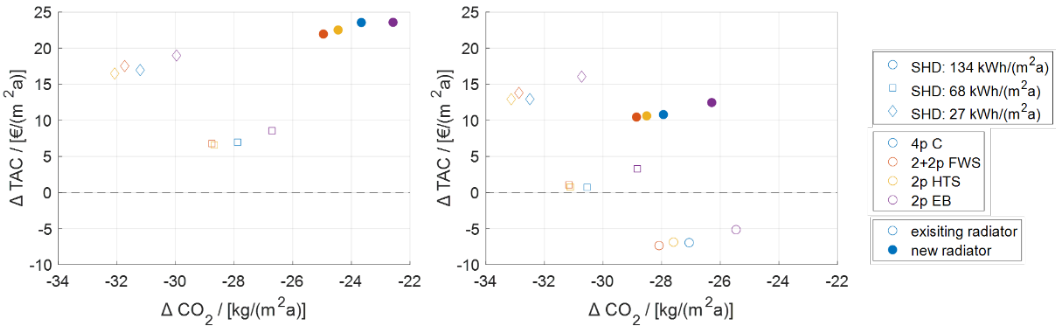

Figure 8. Difference between total annual costs (TAC) and CO_2-emissions compared to the reference case (new flow-type gas boiler, non-renovated case), based on Fig. 5.

The investment costs for thermal renovation (including ventilation with heat recovery) are significantly higher than the HP system costs (for SH and DHW), even when replacing radiators. Total investment costs range from about 240 EUR/m² to 940 EUR/m² for the 4LC variant. The difference in total investment costs between BAU (OIB f_{gee}) and non-renovated is relatively small: higher investments in the building envelope are partially offset by lower HP system costs. The IC of BEST are significantly higher mainly because of the MVHR. However, the picture changes when considering the total annual invest costs (annuity). They are lowest for OIB f_{gee} and the difference to BEST (EnerPHit) reduces because of the long service life of the thermal envelope (windows and thermal insulation).

The overall lowest TAC is the non-renovated building with the existing radiator and the B/W-HP. TAC are even negative for the non-renovated case (with the optimistic assumptions for the B/W HP). However, it is important to remark that B/W-HP is not always (i.e. everywhere) possible and depending on the ground conditions, costs could significantly differ from the assumed ones. The total annual costs of the non-renovated building (with radiator replacement only) is the lower only than BEST in the case of B/W HP, with a difference of ca. 10 EUR/(m² a). Important for the feasibility of a variant is the required space for the HP (see Fig. 9) and the sound emissions (in particular in case of A/W-HP). In the non-renovated case, the required HP capacity leads to a HP size and sound emissions, that would not be feasible in denser neighborhoods. Therefore, in spite of the higher costs, thermal renovations are required to enable switching from fossil to HP based heating systems. If a thermal renovation is required, then the deep thermal renovation (BEST) is recommended.

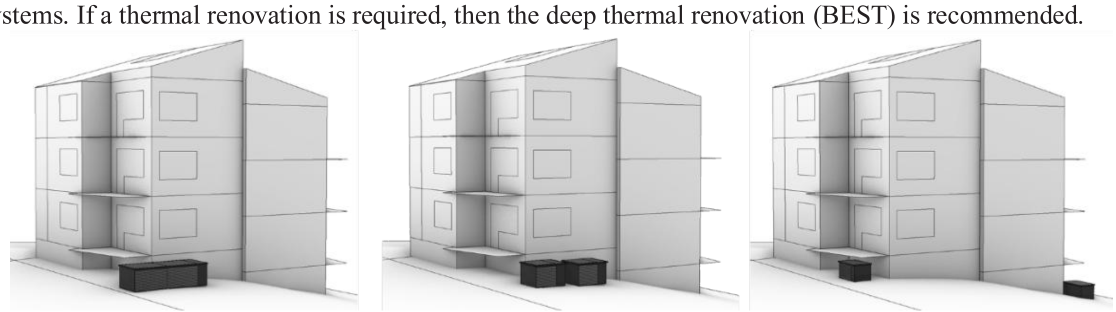

Figure 9. Required size of a A/W-HP for the case non-renovated (left with one ALM 10-50), BAU (center with two ALM 6-15) and BEST (right with two ALM 2-8), acc. to Tab. 4

Tab. 5 summarizes the system seasonal performance factor (SPF) of the different HP concepts, depending on the quality of the building (renovation level). System SPF are higher for the B/W HP compared to the A/W HP. The system SPF is higher in case of the non-renovated building (None) and lowest for the deep renovation (BEST), however the electricity demand is significantly lower in case of BEST. With respect to the HP system, depending on the renovation case either the 2+2p system with FWS or the 2p system with HTS is better.

Table 5. System SPF of the A/W- and the B/W HP for the different renovation cases. The SPF for the "None" case is calculated with new radiators, while for "BAU" and "BEST," it is calculated using the existing radiators.

		None	BAU	BEST
SPF A/W HP	4p C	2.0	1.9	1.6
	2+2p FWS	2.3	2.1	1.9
	2p HTS	2.2	2.1	2.1
	2p EB	1.8	1.6	1.2
SPF B/W HP	4p C	3.2	3.0	2.4
	2+2p FWS	3.7	3.4	2.8
	2p HTS	3.5	3.4	3.2
	2p EB	2.6	2.2	1.5

4. Conclusions

Using a renovation case study in Austria, the suggested workflow for a simulation-based integral planning process was demonstrated. An improved building envelope significantly reduces electricity consumption, regardless of the distribution or HP system (from slightly above 100 kWh/(m² a) in the worst-case, to below 40 kWh/(m² a) in the best-case). In the non-renovated building, electricity consumption in the best-case is still significantly higher than in the worst-case with thermal renovation. Replacing radiators only offers advantages in the non-renovated buildings (the flow temperature can be reduced from approximately 65 °C to 55 °C).

B/W-HPs are more efficient than A/W-HP but the differences decrease with improved building envelopes. Systems with electric boilers for DHW have significantly higher electricity consumption and are therefore not recommended. All-electric systems (e.g., decentral direct heating systems and electric instantaneous water heaters) were not considered in the analysis because they perform significantly worse in terms of energy efficiency and operating costs compared to central HP systems and, in particular, cannot be considered future-proof given the current electricity mix and the applicable efficiency requirements.

B/W-HPs require lower electrical grid connection capacities compared to A/W-HPs, which can reduce fixed costs (provided there is a capacity charge). However, it is noteworthy that the assumptions for the B/W-HP are rather optimistic and depending on the boundary conditions of the specific location and without the possibility of regeneration, the performance could be closer to that of A/W-HPs. Here, more detailed investigations are recommended. In addition, renovation level has even more significant impact on the electric grid connection capacity, for example in case of BEST the load is three times less than the non-renovated.

Thermal renovation of the building envelope is the key for reducing LCC and CO_2 emissions and it is important to highlight that SPF as indicator can be misleading. The choice of the HP system influences both overall efficiency and costs and should be individually planned and optimized. Despite the higher investment costs, B/W-HPs, with their higher efficiency, should be more strongly promoted, as they lead to lower consumption and reduced peak loads in winter, thus making a significant contribution to the energy transition. In the future, when flexible electricity tariffs become dominant, they could also offer cost advantages.

Non-renovated buildings will incur additional investments for replacement over the period under consideration (e.g., window renovation or replacement) without necessarily delivering CO_2 benefits – unless higher-quality components are selected. This needs to be considered in decision-making.

During the pre-design and design process different renovation levels, HP concepts (HP source, HP system concept and heat emission system) have to be analyzed, compared and optimized in terms of energetic and economic performance - including a sensitivity analysis with respect to (monthly) electricity cost and CO_2 prices. An innovative integral planning method, software and knowledge-based is required to foster the installation of HPs in building renovations with increased efficiency for the transition to renewable energy system. Furthermore, reaching near net-zero energy performance by integration of renewable electricity from rooftop and façade photovoltaics should be shown. Skilling up professionals will bring the best practice to reality.

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