14th IEA Heat Pump Conference
15-18 May 2023, Chicago, Illinois

Impact of the European Building Energy Requirements on the Heat Pump Market

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Abstract

To reach the climate targets set for 2040, it is necessary to increase the efficiency of the building stock and foster the electrification of the buildings' heating system. In this framework, heat pumps will play an important role, in the process of phasing-out fossils. Nevertheless, to enable the efficient operation of a heat pump for heating purposes, low supply temperatures are required. This means that the building should be renovated (i.e. to reduce the heating demand) and the emission system should allow for low supply temperature operation.

In this work, an overview of the development of energy policies in Europe is provided to show the requirements in terms of heating demand. In addition, the effect of the renovation deepness on the heating demand and heating load is shown using a reference multifamily building located in Potsdam (DE). For each renovation scenario, the room-wise heating load is calculated and the effect of the heating load reduction due to renovation in combination with different hypotheses for the sizing of the radiators on the design supply temperature and heat pump performances is described.

Selection and/or peer-review under the responsibility of the organizers of the 14th IEA Heat Pump Conference 2023.

Keywords: Type your keywords here, separated by semicolons

1. Introduction

1.1. Energy-efficient buildings - development of requirements

The European Union (EU) aim at limiting the environmental impact of buildings through specific policies ([1] presents a good overview of the history of European standardisation, while in [2] the overview is extended to standardisation in China and the USA). A clear example is the recast of the Energy Performance of Buildings Directive (EPBD) [3]. According to the EPBD recast, all new buildings must be nearly zero energy buildings (nZEB) by the end of 2020. Nevertheless, the definition of nZEB is up to each Member State. However, the common aspect is to achieve very high energy efficiency and to use as much as possible on-site (or nearby) renewable energy to meet the remaining low energy demand of the buildings. In addition, Member States should develop a methodology for cost optimality. The history of the definition of nZEBs in the European context is shown in Fig. 1.

The national nZEB definitions are quite different and hardly comparable [4] and in both Germany and Austria the current level of the requirements fail to achieve the goal of significantly improving energy efficiency in the building sector and thus reducing primary energy consumption and CO_2 emissions. Technical development would allow achieving the Passive House standard already 30 years ago demonstrating that the implementation of energy-efficient buildings does not present any technical hurdles. Calculated over the life cycle, such buildings are also more economical than buildings realised according to the current level of requirements [5]. Fig. 1 shows the development of energy efficiency requirements for buildings in Germany and Austria compared to the Passive House Standard. The heating demand was calculated based on a terraced

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house (Passive House Kranichstein). The first German standard dates to 1977, in which the maximum U-value of the individual building components was defined. This was followed by the Heat Conservation Ordinance (WSchV 95) that introduced the calculation of the energy balance and a maximum value for the annual heating demand.

If the tightening of the requirements had continued at the same pace, the maximum heating demand (HD) would have reached the passive house standard already in 2013.

The first Energy Saving Ordinance (EnEV) came into force in 2002 and replaced the annual heating demand as a criterion with the primary energy demand of the building compared to a reference building. In addition, non-renewable primary energy factors were defined.

In Austria, the development towards energy-efficient buildings took place somewhat later: based on the Energy Performance Certificate Act (EAVG) in 2006, the guideline OIB-6:2007 imposed a limit on the HD. The level was then tightened in 2010 and 201. In 2014, the National Plan for the definition of nZEBs in Austria was published (the review took place in 2018). Since the introduction of the guideline OIB-6:2015, the so-called dual path (see Fig. 1 fgee and EEB) has been defined in Austria. With the new version of the OIB guideline, non-renewable primary energy is used as an indicator and excludes household electricity in residential buildings).

The requirements for the thermal quality of the building envelope have remained essentially unchanged since OIB-6:2007 (external wall max. U = 0.35 W/(m² K)).

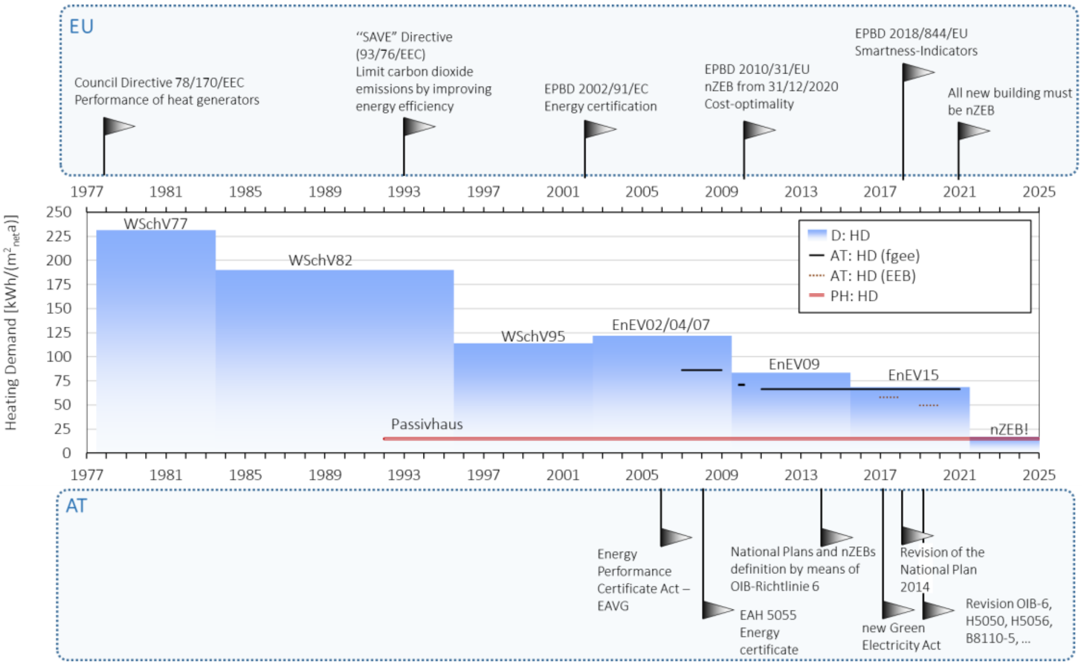


Fig. 1: Heating demand according to the German legal framework compared to the passive house standard [6] and history of nearly zero energy buildings - nZEBs (Directive 2010/31/EC) [7].

In the United Kingdom the Energy Performance of Buildings (England and Wales) Regulations 2012 set the Energy Performance Certificates (EPCs) as a requirement whenever a building is built, sold or rented and, in some circumstances, refurbished. With the Energy Efficiency Regulations 2015, it will be illegal to lease buildings with a EPC rating of F or G [8], [9].

In Spain, the procedure for the calculation of the EPC are defined by Royal Decree 235/2013 [10]. The Royal Decree-Law 14/2022 foresee a wide range of energy saving measures (e.g. limitation of the heating and cooling set points to 19°C and 27°C respectively, encouraging electrifications and penetration of renewables, etc..).

In Italy, the EPBD 2002 was implemented with Decreto Legislativo 192/2005, which introduces the criteria and method for the calculation of the EPC. The DM 26/06/2015 define new rules for the calculation of the EPC and the minimum energy requisite for new and renovated buildings [11].

In Sweden, the Energy Performance Certification Act (Sw. Lag (2006:985) om energideklaration för byggnader) makes the EPC mandatory for certain building categories. A minimum standard (i.e. from A to G) is introduced for buildings classified after 1/1/2014. In 2020, the PBF and the BBR were revised tightening also the requirements for energy performance for buildings. The Act (2006:985) on energy performance certificates for buildings as well as Boverket's BED was updated in March 2021, regarding inspections [12].

As non-EU-country, Switzerland is not obliged to implement the EPDB, nevertheless Switzerland as member of CEN, agreed to adopt all EU standards [13]. The MuKEn 2014 define the sample regulation used as a reference for the application of the energy regulation in the different cantons.

In Belgium, the first EPB ordinance was defined in 2007. In 2015 a new ordinance (COBRACE) came into force, which transposes the EPBD 2010 [14].

A deep comparison of the nZEB implementation in different European countries is also presented in [4], [15] and [16].

1.2. Plus, zero or near-zero energy building

Various definitions of highly efficient buildings (i.e. good quality of the building envelope) in combination with a high share of renewable energy (usually PV) are in use with the aim of achieving zero, almost zero or plus energy. These definitions sometimes differ significantly with regard to the boundary of the energy balance (space heating, domestic hot water, auxiliary energy, household electricity) and the type of balancing. Plus, usually refers to net-plus, i.e. annual balance. This is possible in very efficient buildings such as the Passive House with a PV system of about 5 kWp; in multi-storey residential buildings, net-zero is usually no longer possible from about 4 storeys upwards if household electricity is also taken into account. It is important to pinpoint that a net-zero building still requires a considerable amount of energy from the grid in winter. According to [17], an NZEB could theoretically be a building with relatively high U-values and consequently a high heating demand having a correspondingly large photovoltaic (PV) system. Such an NZEB would generate a large PV surplus in summer while still having a high grid load during the heating period (so called "winter gap").

The final energy demand and primary energy demand of different building concepts and energy standards are shown in Fig. 2 [18]. In terms of primary energy demand for heating and domestic hot water (DHW), the Solar Active House with a specific limit value (based on the net floor area) of 15 kWh/(m² a) is slightly below that of the Passive House (i.e. 18.5 kWh/(m² a)), this considering that the building is supplied with a heat pump (HP) characterized by an annual performance factor of 2.4 (for heating and DWH purposes and including the losses of the storage and distribution system [19]).

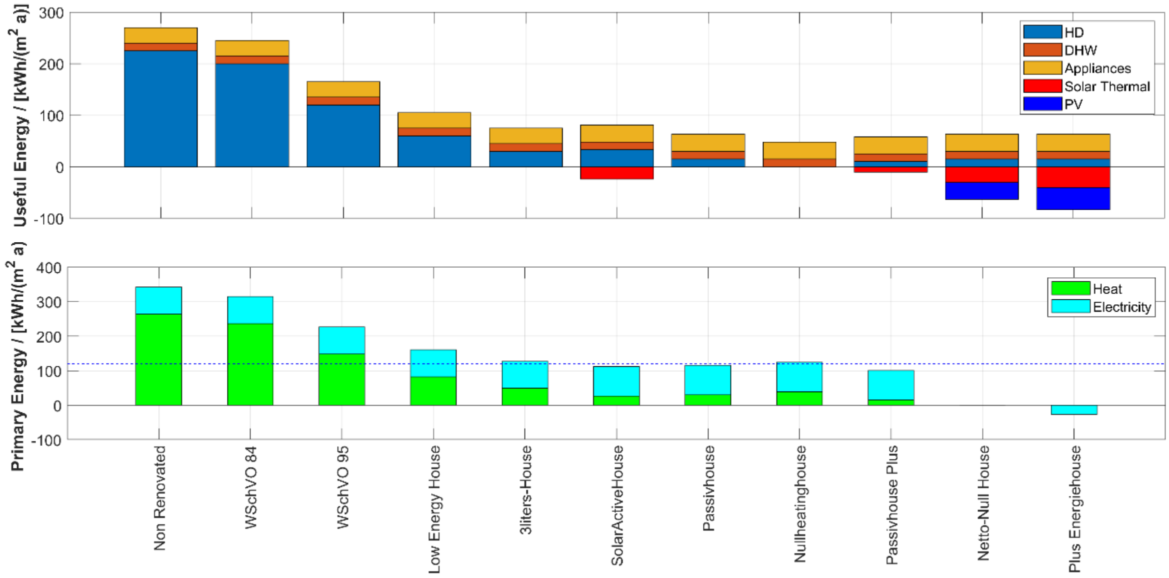


Fig. 2: Final energy demand (top) and primary energy demand (bottom) of different building concepts. The results are normalized with a reference area of 140 m². The following inputs are used for generating the results of the figure: domestic hot water (DHW) 25 l/d/P at 60 °C and 4 persons, no heat losses through distribution and storage; household electricity demand: 3500 kWh/a [18].

Passive House Institute set the limit on the primary energy to 120 kWh/(m²energy reference area a) for heating, domestic hot water, technical and household electricity requirements (incl. ventilation and auxiliary power). In addition, since 2015, the Passive House Standard is assessed with the indicator PER (Primary Energy Renewable)[20].

1.3. Role of Heat Pump

As highlighted in [21], heat pumps are the driving technology for the decarbonization of the heating in the building sector and it is foreseen that the number of heat pumps installed globally will rise from 180 million to 600 million in 2030. This in combination with the renovation of the building stock will enable the transition towards a higher share of renewable energy in the electricity grid (see also [22]). Heat pump is a very flexible and efficient technology that as exhaustively reported in [23] can work with different sources, can be applied at different levels (i.e. district, centrally building or block-wise, decentral flat-wise) and can be used for different services (i.e. heating, domestic hot water, cooling, mechanical ventilation in combination with an exhaust or extract air heat pump).

Nevertheless, some challenges have to be overcome to enhance the application of heat pumps. According to [21] the main challenges are: high upfront, operating cost and emission depending on the electricity mix, space restrictions, heating distribution system, low efficiency of heat pump in combination with high-temperature radiators, permission to install the external unit due to visual and sound reasons, social acceptance.

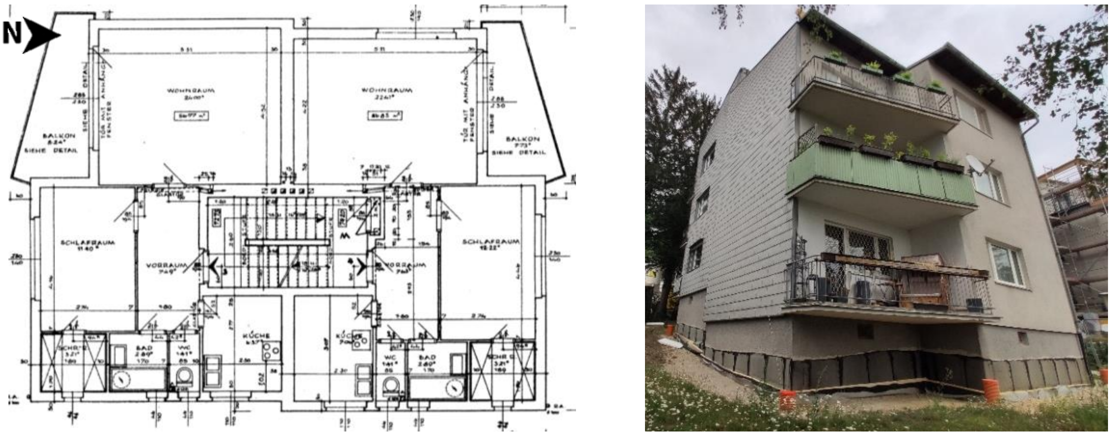
New heat pumps, with adapted refrigerants might help to improve the performances at higher supply temperatures [24]. Nevertheless, the COP will inevitably and drastically decrease as the temperature lift increases (see [25], Figure 58 for a comparison of performances at low and medium temperature level of heat pumps using different refrigerant fluids). In addition it is important to highlight that the performances of the heat pumps under real operating conditions are typically lower compared to the declared performances of the manufacturer [19].

2. Methodology

2.1. Reference Building

The reference building is a typical Austrian multi-family house composed by 3 floors and six flats of 56.8 m^2. The total net floor area of the building is 340.8 m^2 while the total energy reference area is 364.5 m^2. Within this work, the results will be presented using the net floor area as a reference. The walls of the building are made with hollow brick construction, while the roof and floor core construction are based on concrete concave boards.

In Fig. 3 the floor plans and one picture of this building are reported.



(a) (b)

Fig. 3: (a) Floor plan; (b) Picture of the southwest side of the building.

With regards to the weather data, the Test Reference Year (TRY) of Potsdam (generated using Meteonorm v8.1 [26]) is used for the analysis within this work (see Fig. 4).

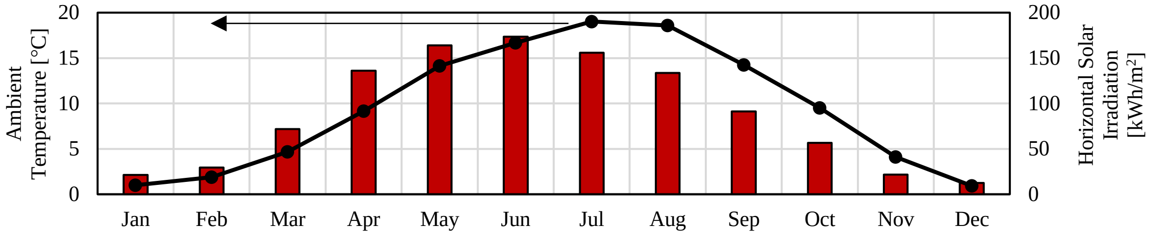


Fig. 4: Monthly average ambient temperature (black line) and monthly horizontal solar irradiation (red columns) for the TRY of Potsdam.

2.2. Renovations

The renovation deepness is very heterogeneous in existing buildings, in fact step wise renovation are often performed. In [27] (see Figures 14-16) an analysis of the average U-values of walls, roof and windows for 45 buildings built between 1979 and 2005 is presented. From this analysis it can be seen that buildings built in the same period can be renovated with very different insulation levels. For this reason in this work, different renovation scenarios are considered for the envelope of the reference building and an overview is provided in Table 1, where the U-values of the building envelope are reported as well as the average U-value (i.e. Ht') considering an envelope area of 779.2 m^2 and the equivalent ventilation rate (which is reduced when a mechanical ventilation system with heat recovery is applied).

Table 1: Overview of the renovation scenarios for the envelope of the reference building.

Renovation scenarios		1	2	3	4	5	6	7	8	9	10	11	12	13
U-Roof	[W/(m^{2}K)]	1.46	**0.37**	**0.16**	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16
U-Wall N		1.25	**0.49**	0.49	0.49	0.49	0.49	0.49	0.49	0.49	**0.24**	0.24	0.24	**0.15**
U-Wall E		1.25	**0.49**	0.49	**0.12**	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12
U-Wall S		1.25	**0.49**	0.49	0.49	0.49	0.49	0.49	0.49	**0.24**	0.24	0.24	0.24	**0.15**
U-Wall W		1.25	**0.77**	**0.22**	0.22	0.22	0.22	0.22	0.22	0.22	0.22	**0.13**	**0.22**	**0.13**
U-Floor		1.17	1.17	1.17	1.17	1.17	1.17	**0.27**	0.27	0.27	0.27	0.27	0.27	0.27
U-Window S		3.00	**1.92**	1.92	1.92	1.92	1.92	1.92	1.92	**1.55**	1.55	1.55	**0.80**	0.80
U-Windows E		3.00	**1.92**	1.92	1.92	**0.80**	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80
U-Windows N		3.00	**1.92**	1.92	1.92	1.92	1.92	1.92	1.92	1.92	**1.55**	1.55	**0.80**	0.80
U-Windows W		3.00	**1.92**	1.92	1.92	1.92	1.92	1.92	1.92	1.92	1.92	1.92	**0.80**	0.80
Thermal Bridges	[W/(m K)]	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	**0.05**	0.05	0.05	0.05
Ht'	[W/(m$^2_{envelope}$ K)][1]	1.59	0.97	0.76	0.70	0.69	0.69	0.51	0.51	0.47	0.39	0.37	0.32	0.29
Ventilation	[1/h]$_{equiv}$	0.27	0.27	0.27	0.27	0.27	**0.17**	**0.27**	**0.17**	0.17	0.17	0.17	0.17	0.17
Efficiency of the ventilation heat recovery	η [-]	0.00	0.00	0.00	0.00	0.00	0.75	0.00	0.75	0.75	0.75	0.75	0.75	0.75

The yellow marked cells of Table 1 highlight the changes made in one renovation case compared to the previous one to facilitate readability. The first case corresponds to a completely non-insulated building, the second case introduces a few centimetres of insulation material in all the structures and double-pane windows. In all the following cases other improvements to part of the envelope and/or the ventilation system are introduced leading to an always more efficient building. The only exception is between cases 6 and 7 where the envelope is improved but the ventilation system has no heat recovery. The set point temperature is considered to be 20°C[2].

2.3. Heating and Domestic Hot Water demand and Load calculations

For each renovation scenario, the building envelope is designed and the heating demand (HD) and load (HL) for the whole building and flatwise are calculated using the Passive House Planning Package PHPP [28]. In addition, the whole building is evaluated by means of dynamic simulation using the carnotUIBK toolbox [29] developed in Matlab/Simulink to assess the dynamic heating demand (on 10 min basis) of the building throughout the whole year.

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[1] $H_t' = \frac{\sum_i A_i \cdot U_i}{\sum_i A_i}$ where i are all the parts of the thermal envelope (i.e. walls, windows, roof, floor) and the thermal bridges.

[2] To assess the real energy demand the prebound effect should be considered for low insulated buildings [35].

PHPP is a quasi-steady-state tool based on Standard ISO 13790:2008 [30] and it has been shown that it can accurately predict the HD of the building [31]. In addition, PHPP can calculate the HL of the building, but in contrast to the standard EN 12831-1 [32], it accounts also for heat gains and considers two different weather scenarios (i.e. cold and sunny day and moderately cold but overcast day).

Therefore, for the sizing process of the radiators, the room-wise heating load is calculated according to the standard EN 12831-1 [32] for each renovation scenario.

As regards the DHW profile, the tapping cycle M described in EN 16147:2017 [33] is used. A reduction factor of 0.625 (resulting in an energy demand of 3.7 kWh/(flat day)) is applied considering an average of 2.5 persons per flat resulting in the profile reported in Table 2. A supply temperature of 55°C is considered for the DHW preparation due to legionella requirements.

Table 2: Hourly useful energy demand for DHW preparation for the whole building.

Hour of day	1-6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22-24
kWh	0	6.04	1.58	0.79	0.39	0.79	1.18	0.00	0.39	0.39	0.39	0.00	1.18	0.39	2.76	5.64	0.00

2.4. Dimensioning of Radiators and supply temperature evaluation

Three different scenarios are considered for the sizing of the radiators: radiators sized in the renovation scenario 1 with a supply temperature of 90°C, radiators sized in the renovation scenario 2 with a supply temperature of 90°C and radiators sized in the renovation scenario 8 with a supply temperature of 45°C. All of these three cases are calculated considering once the room-wise HL according to EN 12831-1 [32] without reheating power and once considering a reheating power of 12 W/m^2.

Since the radiator exponent could range from 1.2 to 1.4 depending on the radiator model and the temperature difference between supply and return over the radiator could range between 10 K and 40 K (except for the low-temperature radiators, where the ΔT could range between 5 K and 10 K) the sizing of the radiators for the different scenarios is performed considering 10 different exponents from 1.2 to 1.4 with a step of 0.02 in combinations with a ΔT ranging from 10 K to 40 K with a step of 10 K for the high-temperature radiators and ranging from 5 K to 10 K with a step of 5 K for the low-temperature radiators.

In the first step the radiators are sized for each room ($\mathrm{n_{el,room_i}}$) using equations (1) knowing the room-wise reference HL ($\mathrm{HL_{Ref_{room_i}}}$), the nominal power of each radiator element[3] ($\mathrm{P_{nom}}$), the radiator exponent n, the reference temperature difference (fixed to 50 K) between the average radiator temperature and the air temperature ($\Delta\mathrm{T_{ref}}$)and knowing the supply and return temperature to the radiator by means of equation (2) it is possible to calculate the logarithmic temperature difference ΔT_{log}.

$$\mathrm{n_{el,room_i}} = \mathrm{ceil}\left(\frac{\mathrm{HL_{Ref_{room_i}}}}{\mathrm{P_{nom}}}\right) \cdot \frac{1}{\left(\frac{\Delta\mathrm{T_{log}}}{\Delta\mathrm{T_{ref}}}\right)^{\mathrm{n}}} \tag{1}$$

$$\Delta T_{log} = \frac{(T_{sup}-T_{air})-(T_{ret}-T_{air})}{\ln\left(\frac{T_{sup}-T_{air}}{T_{ret}-T_{air}}\right)} \tag{2}$$

Sizing the radiator with different ΔT implies different dimensions (i.e. pipe diameter) of the distribution system as for a given reference power different ΔT are achieved by changing the mass flow. Therefore for every ΔT used during the sizing process, the diameter of the pipe serving one flat is determined using equation (*3*) considering a speed of 0.5 m/s. Considering that this system (distribution and emission) is kept constant during the following renovation steps it is considered that the water velocity can be increased up to 1.5 m/s avoiding noise problems but helping to reduce the ΔT and therefore the supply temperature after the renovation.

$$\dot{\mathrm{m}}_{flat} = \frac{\mathrm{HL_{Ref_{flat}}}}{cp_{water}\,\Delta T} = v_{water} \cdot \rho_{water} \cdot \pi \left(\frac{d}{2}\right)^2 \tag{3}$$

For each subsequent renovation (with respect to the sizing case) knowing the HL of each room, and the number of elements of the radiator, the ΔT_{log} can be calculated by reversing equation (1). Knowing the minimum and maximum water mass flow and the HL of the renovated flat, the ΔT over the radiator can be determined inverting equation (3) and knowing ΔT_{log} and ΔT the supply and return temperatures can be calculated using equation (2).

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[3] This is fixed to 100 W as changing $\mathrm{P_{nom}}$ will linearly influence $\mathrm{n_{el,room_i}}$ without changing the final conclusions on the minimum required supply temperature. $\mathrm{P_{nom}}$ influences the dimension of the radiator that is not fixed within this study.

At this point for each renovation case, a set (i.e. 44 cases for the high radiator temperature and 22 cases for the low-temperature radiator) of possible supply and return temperatures are obtained (considering the different sizing possibilities varying ΔT and n and the mass flow rate). In the results section, for sake of simplicity, the minimum supply temperature (that will be obtained when the radiators are sized with the highest ΔT, the minimum exponent[4] and using the maximum mass flow rate) and the maximum supply temperature (that will be obtained when the radiators are sized with the lowest ΔT, the maximum exponent[4] and using the minimum mass flow rate) are shown and used for the evaluation of the heat pump performances.

2.5. Heat Pump performance evaluation

To estimate the impact of the renovation scenarios and radiator sizing on the performances of a central air to water Heat Pump (HP) a Carnot-based approach is used considering a conservative Carnot performance factor of 0.35 [23]. The building-wise heating demand for each time step (i.e. 10 min) is defined by means of the dynamic building simulation and the ambient temperature is known from the TRY. For each sizing scenario of the radiators (i.e. radiators sized in renovation scenario 1, 2 or 8 considering or not the reheating power due to intermittent operation) a maximum and minimum supply temperature is defined for each renovation scenario and this is used as a constant throughout the year in equations (4) and (5) to calculate the COP and electricity demand of the HP.

$$COP(t) = \eta_{Carnot} \cdot \frac{T_{supply}}{T_{supply} - T_{ambient}(t)} \tag{4}$$

$$P_{el,HP}(t) = \frac{HL_{building,sim}(t)}{COP(t)} \tag{5}$$

Only the cases in which the required supply temperature of the heating system is below 60°C are considered compatible with a HP operation.

As regards the DHW preparation, equations (4) and (5) are used considering T_{supply} equal to 55°C and instead of $HL_{building,sim}(t)$ the DHW demand shown in Table 2 is used.

3. Results

3.1. Heating demand and Heating Load for the different renovation scenarios

Fig. 5 shows the HD calculated using the PHPP flat-wise (i.e. for each of the six flats), PHPP building-wise and by means of dynamic simulation for the whole building. From here it can be noticed that the annual HD predicted by the building-PHPP presents a good match with the annual results of the dynamic simulation with a relative deviation of maximum 8% for the renovation scenario 1.

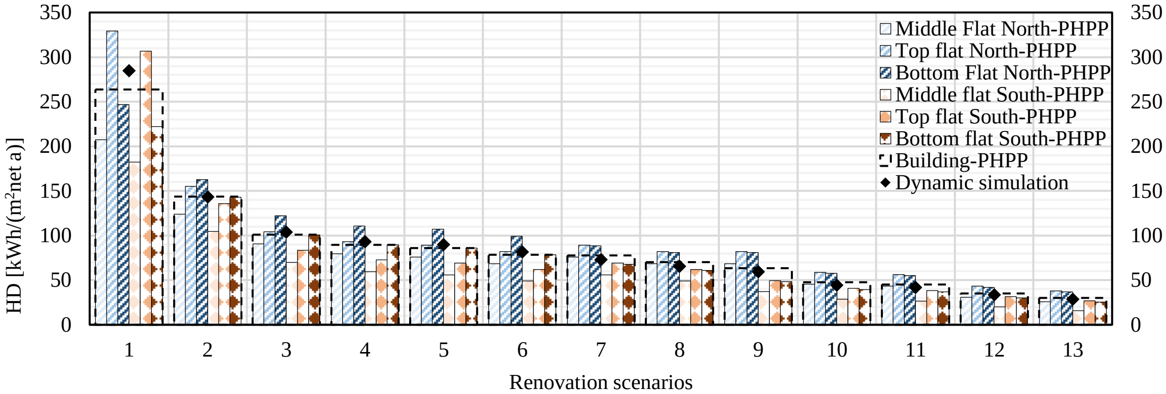

Fig. 5: HD calculated with the PHPP-flat-wise, PHPP-building-wise and by means of dynamic simulation for the whole building for all the renovation scenarios.

In addition, it can be seen that the HD of the flats depends on the orientation (i.e. in this case south-north) due to the solar gains and on the position of the flat within the building. In fact, the middle flats present always

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[4] Higher radiator exponent leads to a higher reduction of the radiator emitted power when the average radiator temperature is reduced. Sizing the radiator with higher ΔT for a fixed supply temperature leads to bigger radiators since they have to deliver the required power with a lower ΔT_{log}.

the lowest HD while the top and bottom flats have the highest HD. Insulating the roof in renovation 1 and 2 leads to lower HD of the top flats compared to the bottom flats. When also the floor is insulated (in step 7), top and bottom flats have similar HD. The best renovation scenario (i.e. 13) leads to a building HD of around 30 kWh/(m$^2_{net}$ a). Fig. 6 reports the HL calculated by means of flat-wise PHPP for all the renovation scenarios. Comparing Fig. 5 with Fig. 6 it can be noticed that the HD and HL follow the same trend. In addition, it is important to mention that in the case of installation of a decentral flat-wise HP solution the HL reported in Fig. 6 should be used for the HP sizing process.

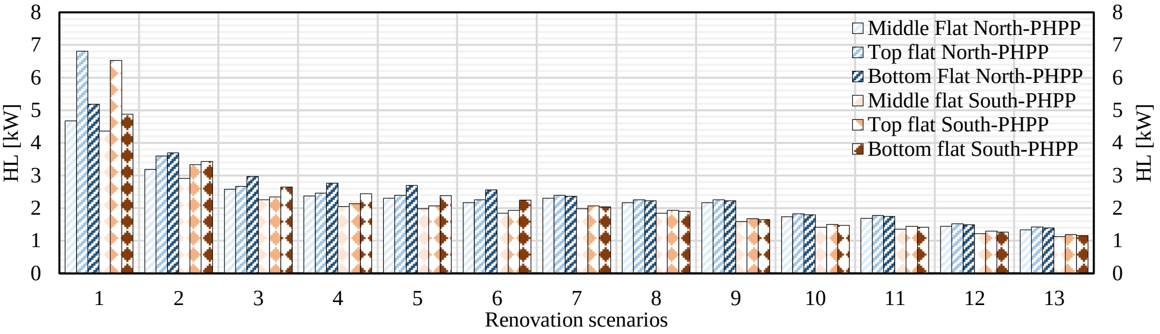
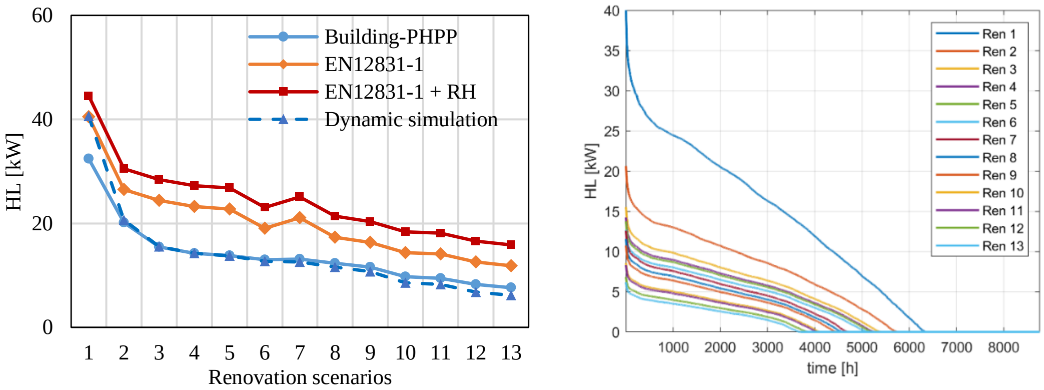


Fig. 6: HL calculated with the PHPP-flat-wise for all the renovation scenarios.

Fig. 7 reports on the left-hand side (a) the HL of all the renovation scenarios calculated with the PHPP-building-wise, the building HL calculated room-wise according to the standard EN 12831-1 considering or not the additional reheating power and the maximum HL derived by means of dynamic simulation. While on the right-hand side (b) of Fig. 7 the load duration curves for each renovation scenario as a result of the whole building dynamic simulation are shown. The HL from the dynamic simulation reported in Fig. 7a corresponds to the maximum of the sorted HL in Fig. 7b (the maximum HL is only required for a few hours a year). From Fig. 7a it can be seen that the HL predicted by the building-PHPP match well with the maximum HL from dynamic simulation except for the renovation scenario 1. It is noteworthy to mention that the HL predicted by the building-PHPP is in average -40% compared to the HL calculated according to EN 12831-1 and -50% when also the reheating power is considered. This is justified by the fact that in the standard stricter conditions are applied for the calculation (i.e. no internal gains, non-heated neighbouring apartments, high ventilation rate, low ambient temperature). These boundary conditions represent the worst-case scenario in terms of HL, which is anyway unlikely to happen at least for long heating periods.

To avoid oversize the HP system, it is recommended to calculate the heating load also through dynamic simulation [34] or using the PHPP (that according to [31] is in good agreement with the results of the dynamic simulation tool). This is important to avoid, a reduction of the HP efficiency due to frequent “on-off” cycles. On the contrary, regarding the dimensioning of the heat emitters, it is recommended [34] to perform a room-wise calculation of the heat load based on the EN 12831. The power needed for the preparation of the DHW has also to be considered during the sizing process of the HP and this depends on the DHW demand, but also the storage capacity and HP operation.



(a) (b)

Fig. 7: (a) HL calculated with the PHPP-building-wise, according to the standard EN 12831-1 considering or not the additional reheating power and by means of dynamic simulation for the whole building for all the renovation scenarios; (b) load duration curve as a result of the whole building dynamic simulation.

3.2. Supply temperature

Fig. 8 shows the possible supply temperature span for each renovation scenario assuming that the radiators could be sized: in the renovation scenario 1 considering the additional reheating power due to intermittent operation of the heating system or not (i.e. Case_1+RH and Case_1), in the renovation scenario 2 (i.e. Case_2+RH and Case_2) and in the renovation scenario 8 with low-temperature radiator (Case_8+RH and Case_8), see also Section 2.4 for additional information. Each case is represented by a temperature span instead of a point as a possible range of radiators was considered (i.e. with different exponent n) sized with different ΔT and run with a range of mass flow that keeps the water speed between 0.5 m/s and 1.5 m/s. The renovation scenarios in which the radiators are installed are exemplarily chosen in this work. In reality, the radiators could be changed/installed in any renovation scenario and could be sized considering different supply temperatures leading to an even wider range of possible supply temperatures required in each renovation.

From Fig. 8 it can be seen that starting from renovation 8 to 13, a wide range of possible supply temperatures could be expected depending on the choice made in the previous renovations of the building. This range goes from low temperatures (i.e. around 35-40°C) up to 80°C (i.e. Case_2).

It is not recommended to apply a monovalent heat pump system if a flow temperature of more than 60°C is required, as its performance would be too low, however, new-generation heat pumps (e.g. propane R290) can reach flow temperatures of 70-75°C. For this reason, the performance of all cases that guarantee a flow temperature below 75°C has been calculated (see Fig. 8, Fig. 9 and Fig. 10). Another noteworthy aspect is that in some countries subsidies for heat pumps are only given if the design flow temperature is below a certain value (e.g. 40°C for Austria). It is important to mention that the temperatures reported in Fig. 8 are design temperatures required in the worst winter conditions and that during the heating season a weather compensation control could be applied reducing the supply temperature based on the ambient temperature allowing higher performances of the HP system and/or longer operation time.

Another aspect highlighted by the supply temperature analysis of Fig. 8 is that renovating only part of the building (e.g. the roof and west-wall from ren. 2 to ren. 3 see Table 1) leads to a reduction in terms of building wise HD and HL (see Fig. 5 and Fig. 6) but might not lower the HL of some rooms, which may then become the bottleneck for the definition of the maximum flow temperature (e.g. see ren. 2 ren. 3 in Fig. 8).

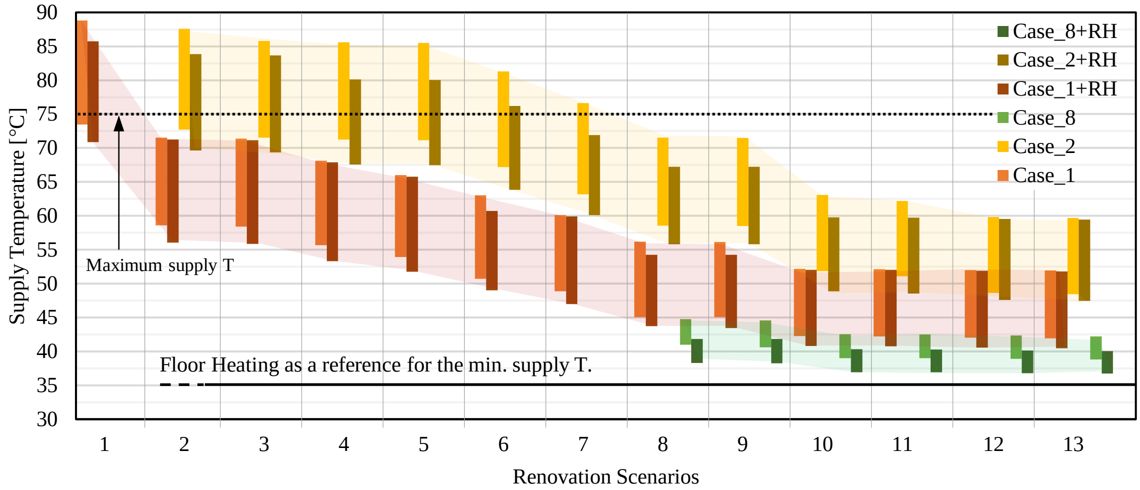


Fig. 8: Design supply temperature ranges required in the different renovation scenarios considering different sizing conditions (i.e. Case 1,2,8 w or w/o reheating (RH)). The different radiator typologies (i.e. different exponent n) sized with different ΔT and considering different mass flows that keep the speed between 0.5 m/s and 1.5m/s define the high of each bar.

3.3. HP performances

Fig. 9 shows the annual electricity demand and Fig. 10 the SPF of the HP for space heating considering the different renovation scenarios (see Fig. 5 and Fig. 7b for annual and sorted heating demands of the different renovations) and the different cases for the design supply temperature (see Fig. 8). The calculation of the electricity demand and SPF of the HP is performed as explained in Section 2.5 considering a Carnot performance factor of 0.35. Only the cases that allow for a supply temperature below 75°C are considered to be compatible with an HP operation and therefore their results are reported in Fig. 9 and Fig. 10. From Fig. 9 it can be noticed that the reduction of the heating demand with increasing quality of the building envelope and ventilation system leads to a reduction of the electricity demand. Nevertheless, for some specific renovation scenarios (i.e. for the considered cases from 8 to 13) the electricity demand could be further reduced of 38% by reducing the supply temperature and therefore increasing the SPF (see Fig. 10). It is important to mention that the absolute difference in terms of electricity demand between the different cases of one specific renovation scenario is reduced when the heating demand is reduced making the building system more robust against non-optimal operation.

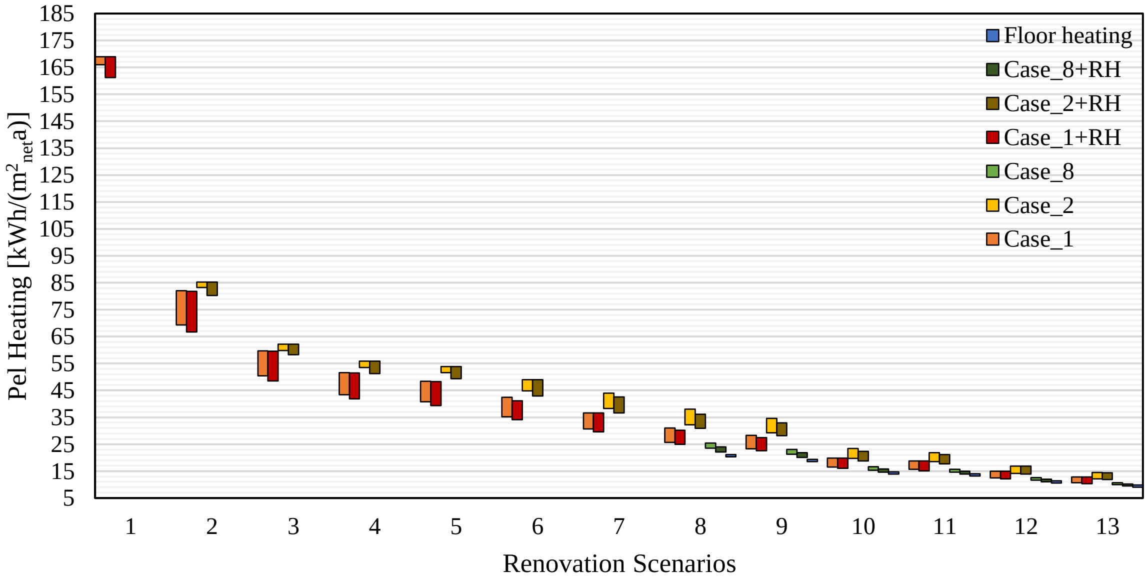


Fig. 9: Annual Electricity demand of the HP for space heating considering the different renovation scenarios and supply temperature.

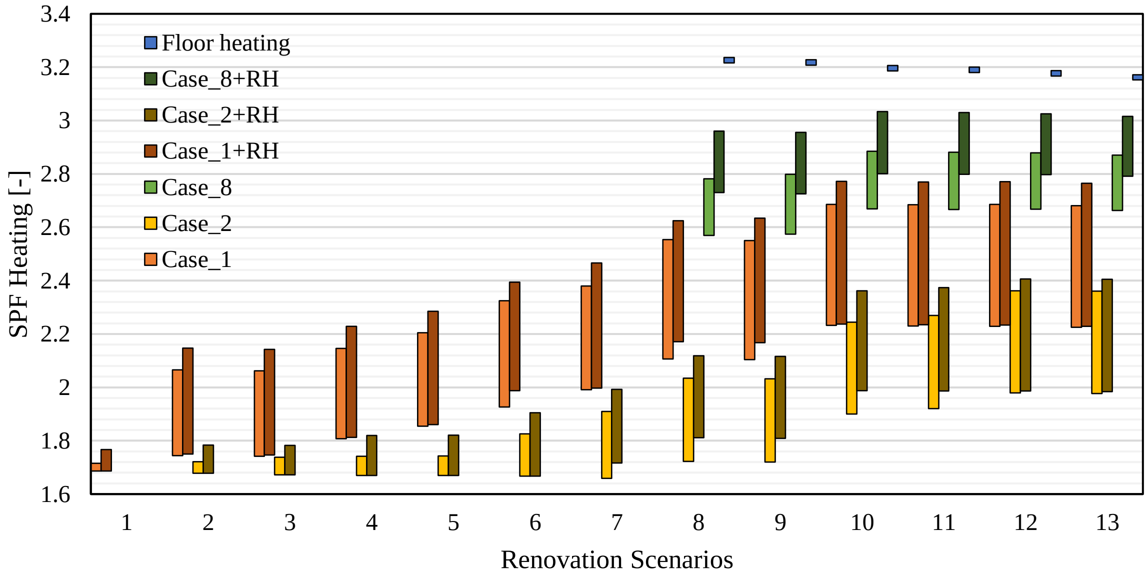


Fig. 10: SPF of the HP for space heating considering the different renovation scenarios and supply temperature.

For all the renovation scenarios the domestic hot water (thermal energy demand of 23.5 kWh/(m^2_{net} a)) is prepared by the air to water HP with a constant supply temperature of 55°C leading to an SPF of 2.5 and an electricity demand of 9.3 kWh/(m^2_{net} a).

4. Conclusions

Within this work, an overview of the development of energy policies in Europe is provided to show the requirements in terms of heating demand. To show the impact of these regulations on the heating load and therefore on the required heat pump size and performance a multi-family house located in Potsdam (DE) is used as a reference. Thirteen different renovation scenarios are analysed. These lead to progressively reduced heating demand and load, which is calculated on the building and flat level using the Passive House Planning Package (PHPP). The performance of the heat pump and the feasibility of installing this type of system in a renovated building highly depend on the required supply temperature, which is defined by the size and typology of the installed radiators and the design heating load. In this study, the room-wise heating load is calculated according to the EN 12831-1 for each renovation scenario and it is used as a basis for sizing the radiators (different radiator exponents, temperature difference for the sizing process and mass flow are taken into account) considering that high-temperature radiators might be installed in the non-renovated case, or in a slightly renovated case and low-temperature radiators might be installed on a moderately renovated case. Based on the different scenarios for the sizing of the radiators a range of possible supply temperatures for each renovation scenario is defined. Finally, the performances of a central air-to-water heat pump with a Carnot performance factor of 0.35 are evaluated using the calculated supply temperature and the heating demand of the building obtained by means of building-wise dynamic simulations.

The results show that the heating load of the reference building, characterized by a net floor area of 340.8 m^2, can be reduced from 32 kW to 8 kW (the heating demand from 264 to 30 kWh/(m^2a)) by means of thermal renovation of the building envelope and the introduction of mechanical ventilation. The heating load flat-wise, for the worst flat, decreases from 6.8 kW to 1.4 kW. This demonstrates the need of introducing more small-size (i.e. micro) heat pumps on the market as their demand in the future will increase.

The analysis of the supply temperature shows that to enable an efficient heat pump operation it is necessary to have highly over-dimensioned radiators, very deep thermal renovation or to have at least a moderate thermal renovation in combination with a replacement of the existing radiators with low-temperature radiators. Depending on the installed emission system, for a given renovation, the SPF of the heat pump could vary between 1.7 and 3.2 leading to a reduction in electricity demand of up to 46%. As expected, the best efficiency is reached with the floor heating system. Also substituting the existing radiators with low temperature radiators (case 8) might highly contribute to improve the SPF. The worst scenario is represented by the case 2 (high temperature radiators installed during a partial renovation e.g. ren. 2). In this case, the radiators are only slightly oversized compared to case 1 (radiators sized for the non-insulated building – ren. 1), thus they do not allow for significant temperature reduction throughout the various renovation levels.

It is also important to remark that a high-quality thermal renovation not only allows an efficient operation of the heat pump but also makes the building-HVAC system more robust against non-optimal operating conditions.

In a future work, the effect of changing radiators only in the bottleneck rooms should be considered, the performances of the system should be analysed also considering a reduction of the supply temperature throughout the year based on the ambient temperature and different heat pump typologies (e.g., air source or ground source heat pumps) with different performances should be included in the evaluation.

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