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DECARBONISATION THROUGH INNOVATION

Low-temperature heating through façade-integrated thermal activation for minimal-invasive heat pump retrofits in residential buildings from the 1960s

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Abstract

The building sector is a significant contributor to global greenhouse gas emissions. However, energy efficiency enhancement measures such as thermal refurbishment and switching to low-temperature heating systems in existing buildings pose considerable challenges. The results presented in this paper originate from an existing building that was refurbished during full operation without requiring the residents to move out for the duration of the refurbishment works. The renovation concept features the substitution of the existing gas-fired heating system with heat pumps, and in connection with this, a more efficient operation of the system at lower flow temperatures. The resulting reduction in heating power of the existing radiators is compensated by adding a retrofitted thermal activation system to the façade of the building. The façade activation has been in operation for two years and its behaviour has been observed via the installed monitoring system. Analysis of the monitoring shows a clear impact of the thermal activation on the façade's inner surface temperature. Furthermore, a heat flow analysis based on temperature measurements reveals a maximum total thermal power of the thermal activation of 17.5 W/m^2_{facade} for the chosen observation period of 23rd-31st January 2025 and the measured amount of heat transmitted via the façade during the heating season 2024/25 was established as 13,190 kWh or 22.5-25.4 kWh/m^2_{facade}. Finally, the thermal power and heat production of the air-to-water heat pumps feeding the thermal activation was established for the heating season via electrical power measurement data as well as an assumed coefficient of performance (COP) and their efficiency via calculating the Seasonal Performance Factor (SPF) for the time period of 10th January – 4th February 2025, resulting in an SPF of 3.9.

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Keywords: air-to-water heat pump ; refurbishment ; radiant systems ; TABS

1. Introduction

Global warming is one of the largest threats to human health, life and prosperity of our time and is mainly caused by anthropogenic activities [1]. The running of buildings in Central Europe, and more specifically Austria, results in significant amounts of GHG emissions, mainly caused by burning fossil fuels in heating systems for space heating and hot water production [2, 3]. The efficiency improvement and decarbonisation of the building sector through thermal refurbishment and heating system substitution is therefore a vital necessity to cut GHG emissions. One of the most promising technologies to decrease GHG emissions origination from building operations is the heat pump technology. Heat pumps use electricity to harvest low-grade heat from the environment, thus operating with efficiencies exceeding 1 (and up to 5 or 6 depending on the heat source) [4] and thus representing a much more efficient solution than conventional combustion systems.

One major challenge in the implementation of heat pumps is the applicability in existing buildings with high heating energy demand and high heating loads. Usually, such high loads are covered using high flow

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temperature levels of above 50 °C. Heat pumps, however, operate most efficiently at flow temperature levels of up to approximately 50 °C, making a switch to a low-temperature heating system necessary [5]. As a consequence, in order to meet the heating demand of the building, an extension of the existing heat release components becomes necessary which in the case of existing and therefore inhabited buildings becomes a major challenge. This paper presents results from the *Sani60ies* research project which aims to address these challenges by developing a novel refurbishment concept which allows the switch from a fossil-fuelled heating system to a heat pump system operating at lower temperatures. This is possible thanks to a retrofitted thermal activation of the building façade which acts as an additional heat release component. All refurbishment work was carried out externally while the building remained in full operation.

The results presented originate from the first of three demo sites and describe the behaviour of the activated façade in the heating season of 2024/25 using air-to-water heat pumps as a heat source. In particular, the effect of the façade activation on the wall's inner surface temperature is established to describe the effect of the thermal activation on the indoor environment. Then, the amount of heat released via the façade is established via a heat flow analysis based on measured temperature data and in part compared with heat meter data. Furthermore, the measured electrical power of the heat pumps and an assumed coefficient of performance (COP) based on the information given in the device's data sheet is used to calculate the thermal power and heat production. Thus, the system's heating power as well as amount of heat released to the building is derived from measurement data.

2. Methods

The results presented in this paper refer to the first of three test case properties studied in the *Sani60ies* project. The data used in the evaluations was collected via the monitoring system in the building and further processed to calculate heat fluxes and heat and power quantities.

2.1. Test case building

The test case building is located in *Große Neugasse* (Vienna, 4th district) and is a residential block dating from 1968 (cf. Figure 1, left). It consists of 20 flats and 2 shops which are distributed over 6 storeys. The conditioned floor area amounts to 1,001.9 m^2. As part of the research project, the building was thermally refurbished and the façade was activated by cutting channels into the existing exterior render followed by laying flexible raised-temperature-resistant polyethylene piping (PE-RT-pipes) into these at a pipe spacing of 30 cm. Then, the channels containing the pipes were closed using render and the thermal insulation was applied. The U-value of the façade was thus reduced from 0.93 to 0.2 W/m^{2}K. The process of installing the pipes is shown in Figure 1 on the right.

Figure 1. The appearance of the building after refurbishment (left) and the process of laying the PE-RT pipes into the channels (right).

The heat generation system for the façade activation consists of 2 *Stiebel Eltron* WPL-A 05 HK 230 Premium air-to-water heat pumps with 5 kW rated heating power (according to EN 14511 for the test conditions A-7/W35) each. These are connected to a 200 l-buffer tank from which the heat is transported to a manifold splitting the heating water into two streams supplying the street and the courtyard sides of the façade activation. The existing radiators in the flats continue to operate as heat release components and were still supplied using the existing gas boiler during the heating season of 2024/25.

2.2. Monitoring system

The monitoring system consists of 3 major parts:

- Temperature measurement of the façade core, indoor and outdoor air conditions, system temperatures in the plant room and system temperatures of every heating circuit in the façade
- Electrical power consumption of the heat pumps
- Heat meters in the plant room to establish the heat generation system's heat production

For the evaluations of the present paper, the temperature data of the façade core and the indoor and outdoor air conditions as well as the electrical power consumption of the heat pumps and the heat meter data are relevant. The façade core temperature $T_{facade,i}$ (sensors T2-T6) is measured at 5 locations on the street side of the building, cf. Figure 2. These are type PT100 temperature sensors connected to a data logger which records mean temperature values at 15-minute intervals. Likewise, the outdoor air temperature T_{out} is measured using a PT100 temperature sensor and logged as 15-minute mean values.

Figure 2. The location of the façade core temperature sensors T2-T6 shown in green on the façade facing *Rittergasse* (left) and *Große Neugasse* (right). The sensor T1 was abandoned in June 2023 and therefore has not been active since then. The piping scheme of the façade heating circuits is shown in red.

In the plant room, temperature sensors were installed to measure the flow and return temperature of the manifold feeding the street side heating circuits (T7 for $T_{flow,GrNeu}$ and T8 for $T_{return,GrNeu}$) as well as heat meters measuring the amount of heat transported between the heat pumps and the connecting pipes to the street side as well as courtyard side façade heating circuits at various positions (cf. Figure 3). The flow and return temperature are also measured using PT100 sensors and logged as 15-minute mean values. The heat meters are *ista* meters featuring ultrasonic transducers and external temperature sensors.

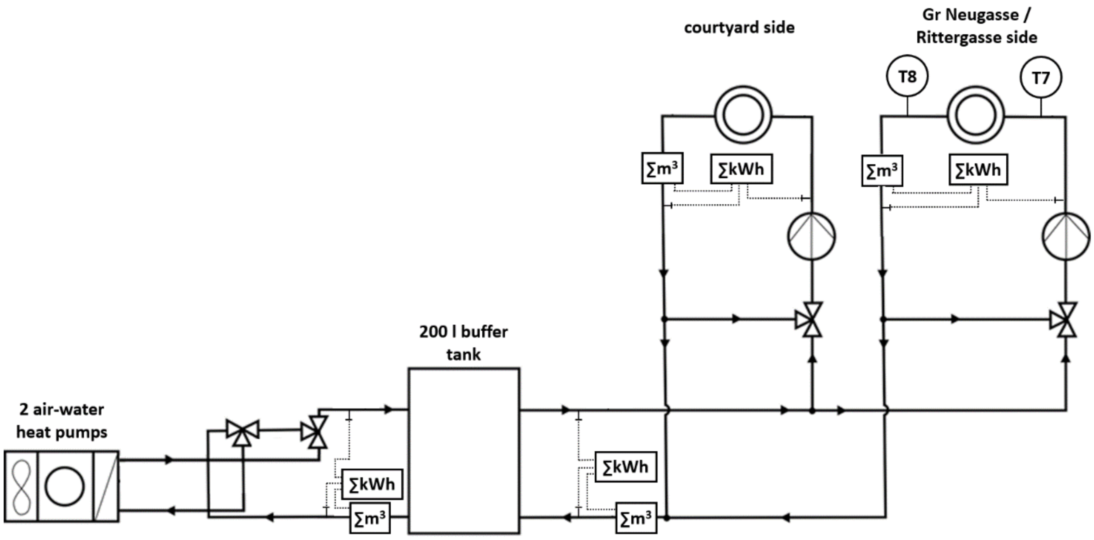

Figure 3. Position of the heat meters and flow (T7) and return temperature (T8) sensors in the plant room.

Indoor conditions are measured by three IoT *Efento* data loggers using PT1000 temperature sensors, of which the first measures the indoor air temperature T_{in}, the second measures the temperature of the inner surface of the activated façade $T_{wall,in}$ (cf. Figure 4, left) and the third measures the surface temperature of the radiator T_{rad} (cf. Figure 4, right). All indoor condition data loggers are located in the room behind the top left window of the façade looking out on Rittergasse (see Figure 2, left). The logged values are also 15-minute mean values.

Figure 4. The installation of the temperature sensors and loggers measuring the façade inner surface temperature $T_{wall,in}$ (left) and the radiator surface temperature T_{rad} (right).

Finally, the electrical power consumption of the air-to-water heat pumps $P_{el,1,j}$ and $P_{el,2,j}$ was measured using two *Fluke* 1734 three phase power measurement loggers featuring flexible Rogowski coil current probes and magnetic voltage probes (cf. Figure 5). The current, voltage and power are logged as 5-seconds average values.

Figure 5. Installation of the electrical power loggers in the switchgear cabinet for both heat pumps.

2.3. Analyses and calculations

For the analysis of the impact of the façade activation on the indoor environment, temperature data for a day with the façade in merely compensatory operation is compared to a day with the façade in over-compensatory operation. According to Schmidt et al. [6], compensatory operation occurs when the temperature of the façade activation (heating water or façade core temperature) is equal to the indoor air temperature, therefore preventing a heat flux from the indoor air into the façade activation. Over-compensatory operation is given when the temperature of the façade activation is higher than the indoor air temperature, therefore resulting in a heat flux from the activation into the room. Thus, compensatory operation only inhibits heat losses from the indoor air into the façade while over-compensatory operation results in the thermal activation acting as a heat release component. The necessary temperature level for over-compensatory operation was selected based on static simulations of the heating system solving the energy balance of the building under various outdoor air conditions described in [7]. These result in a necessary flow temperature of between 32 and 38 °C for the minimum outdoor temperature of -12.4 °C with 50-100 % of the existing radiators in operation. For simplification and as a conservative approach, it was decided to operate the façade heating at a static flow temperature level of 35 °C. The switch to merely compensatory operation during a period in February 2025 with a flow temperature of 22 °C was performed in order to evaluate the impact of the operation mode in the indoor air temperature. For the analysis, it was attempted to select days with similar outdoor air temperature (T_{out}) behaviour based on visual analysis of the outdoor air temperature trajectories. The results for the best match are presented in this paper, for which the indoor conditions are established via visual analysis of T_{in}, $T_{wall,in}$ and T_{rad}.

To describe the thermal behaviour of the façade, a heat flow calculation was conducted based on the temperature measurement data of the façade core temperature, the flow and return temperature of the façade activation and the indoor as well as outdoor air temperature. The heat fluxes from the façade activation directed towards the indoor environment and that directed to the outdoor environment were thus calculated for every time step as:

$$\dot{Q}_{facade,in} = U_{in} \cdot A_{facade} \cdot \left(\bar{T}_{sys} - T_{in}\right) \quad [W] \tag{1}$$

$$\dot{Q}_{facade,out} = U_{out} \cdot A_{facade} \cdot \left(\bar{T}_{sys} - T_{out}\right) \quad [W] \tag{2}$$

U_{in} and U_{out} refer to the U-value of the façade layers between the internal surface and the façade activation and the external surface and the façade activation, respectively, and are assumed as 0.97 W/m^{2}K for U_{in} and

0.246 W/m^{2}K for U_{out}. The activated façade area A_{facade} is 569.6 m^2. The mean system temperature $\bar{T}_{sys}$ is calculated as the arithmetic mean of the façade core temperature measurements (sensors T2-T6) and the flow and return temperature of the heating water fed to the street side heating circuits only. This is due to the fact that no temperature data was available for the courtyard side circuits, however, both sides of the façade activation are operated at the same temperature levels (i.e., no difference in mixing the return with the flow temperature in the pumping and mixing units of the manifold supplying the street and courtyard side) and it is assumed that the measured flow and return temperature levels apply for the whole system. $\bar{T}_{sys}$ is thus defined as:

$$\bar{T}_{sys} = \frac{T_{flow,GrNeu} + T_{return,GrNeu} + \bar{T}_{facade}}{3} \quad [°C] \tag{3}$$

with the mean value of the 5 façade temperature sensors ($n = 5$):

$$\bar{T}_{facade} = \frac{\sum_{i=1}^{n} T_{facade,i}}{n} \quad [°C] \tag{4}$$

The total amount of transferred heat $\dot{Q}_{facade,total}$ is calculated as:

$$\dot{Q}_{facade,total} = \dot{Q}_{facade,in} + \dot{Q}_{facade,out} \quad [W] \tag{5}$$

The results for $\dot{Q}_{facade,total}$ can be roughly cross-validated with the heat meter data. Unfortunately, due to a technical defect of the data logger, temperature data does not exist for the entire heating period. Thus, a timespan with full availability of all temperature data corresponding to a heat meter reading interval was selected for the comparison of $\dot{Q}_{facade,total}$ with the metered heat data. For the calculation of the amount of heat released per m^2 of façade area and conditioned floor area from the heat meter data, the total values were put in relation to the activated façade area A_{facade} and the conditioned floor area of 1,001.9 m^2, respectively.

For the calculation of the thermal power $\dot{Q}_{th,1,j}$ and $\dot{Q}_{th,2,j}$ of the air-to-water heat pumps for every time step j, the measured electrical power $P_{el,1,j}$ and $P_{el,2,j}$ was multiplied by a static COP of 3.45 read from the heat pumps' data sheet for the test conditions A-7/W35 (EN 14511) [8]:

$$\dot{Q}_{th,i,j} = P_{el,i,j} \cdot COP \quad [W] \tag{6}$$

The heat output of the heat pumps $Q_{th,1,j}$ and $Q_{th,2,j}$ was consequently calculated for every time step as:

$$Q_{th,i,j} = \frac{\dot{Q}_{th,i,j} \cdot \Delta t}{3{,}600{,}000} \quad [kWh] \tag{7}$$

with Δt referring to the measuring interval of 5 s. The amount of generated heat for every heat pump i was aggregated for the heating season over all time steps from $j = 1$ to n as follows:

$$Q_{th,i,total} = \sum_{j=1}^{n} Q_{th,i,j} \quad [kWh] \tag{8}$$

The total power of the heat generation system for the façade activation for every time step $\dot{Q}_{th,total,j}$ as well as the total heat generation $Q_{th,total}$ for the entire observation period was calculated as the sum of the values of both heat pumps:

$$\dot{Q}_{th,total,j} = \dot{Q}_{th,1,j} + \dot{Q}_{th,2,j} \quad [W] \tag{9}$$

$$Q_{th,total} = Q_{th,1,total} + Q_{th,2,total} \quad [kWh] \tag{10}$$

Similarly, the amount of electricity consumed per time step and heat pump $E_{el,i,j}$ can be calculated as:

$$E_{el,i,j} = \frac{P_{el,i,j} \cdot \Delta t}{3{,}600{,}000} \quad [kWh] \tag{11}$$

and the total consumed amount of electricity per heat pump $E_{el,i,total}$ and for both heat pumps in total $E_{el,total}$ as:

$$E_{el,i,total} = \sum_{j=1}^{n} E_{el,i,j} \quad [kWh] \tag{12}$$

$$E_{el,total} = E_{el,1,total} + E_{el,2,total} \quad [kWh] \tag{13}$$

Finally, the Seasonal Performance Factor SPF is calculated as:

$$SPF = \frac{heat\ production\ measured\ by\ heat\ meter}{E_{el,total}} \ [-] \tag{14}$$

where the heat pumps' amount of heat produced is established using the heat meter data.

3. Results and discussion

First, the effect on the indoor environment is discussed. Then, a heat flow analysis is conducted to establish the heat fluxes going into the building and to the outside environment. Next, the measured amount of heat supplied to the façade activation is presented and part of it is used to cross-validate the heat flow analysis results. Finally, the electrical power data of the heat pumps is used to calculate the thermal power and heat output of the heat generation system for the heating season of 2024/25.

3.1. The effect on the indoor environment derived from temperature measurements

In order to establish the effect of the thermal activation of the façade on the indoor environment, measured indoor temperature data is compared for a period with the façade in over-compensatory operation at a flow temperature level of approximately 35 °C and a period with the façade in merely compensatory operation at a flow temperature of approximately 23 °C. Figure 6 shows the flow temperature of the heating water fed to the circuits on the street side of the building $T_{flow,GrNeu}$ (T7), the façade core temperatures $T_{facade,i}$ measured by T2-T6 and the outdoor air temperature T_{out} for February 2025. The period of compensatory operation can be clearly seen from the lower flow and façade core temperatures between 12th and 23rd February.

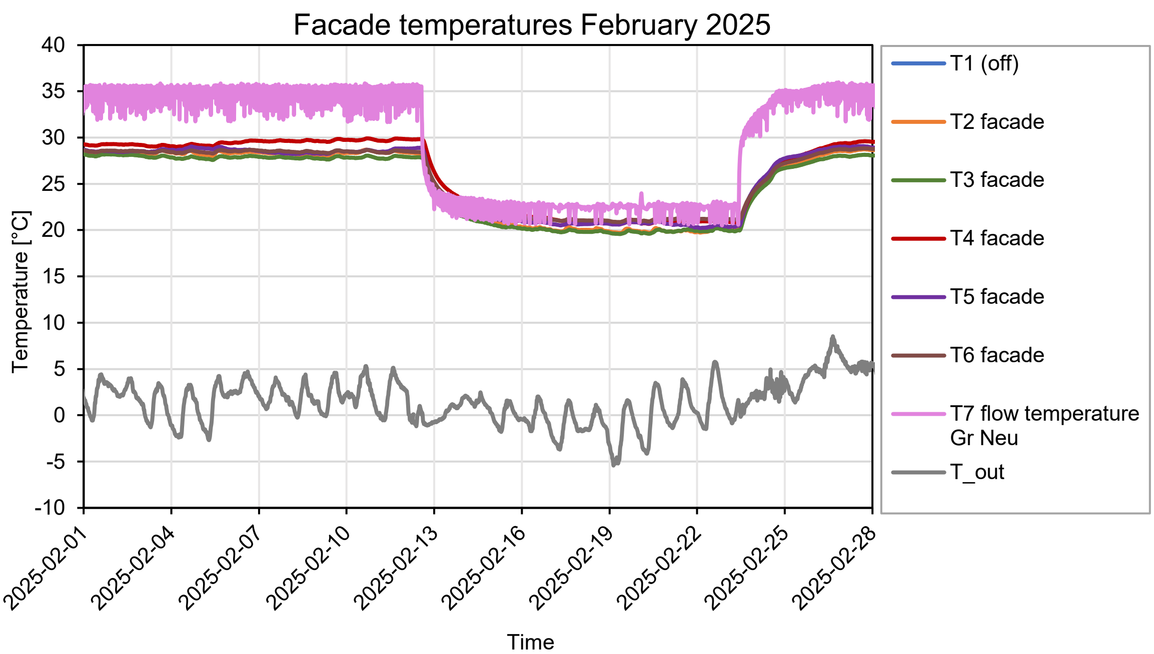

Figure 6. The flow temperature of the heating water fed to the circuits on the street side of the building $T_{flow,GrNeu}$ (T7), the façade core temperatures $T_{facade,i}$ (T2-T6) and the outdoor air temperature (T_{out}) in February 2025.

The comparison for the two days with compensatory and over-compensatory operation is shown in Figure 7. The selected days in the sample period of February 2025 show good agreement for the outdoor air temperature with a maximum deviation of 2 K in the night and during the day a deviation of 1 K at most. The indoor conditions as shown in Figure 7 (right) show altogether lower temperature levels for the day with the façade activation in compensatory operation and, more significantly, a noticeable temperature difference between the indoor air temperature T_{in} and the façade's inner surface temperature $T_{wall,in}$ of approximately 1 K for the day with the façade in over-compensatory operation. Additionally, the radiator temperature T_{rad} was used to verify whether the radiator in the sample room was operating. As can be seen, T_{rad} follows T_{in} on both days, indicating that the radiator is not in use. It should be noted that these are the results for the single available sample flat in the building and the temperature levels therefore only refer to single measurement points in one specific room. Unfortunately, no more residents were prepared to have measuring equipment installed in their flats which is why all results taking into account indoor conditions depend on the measuring points installed in this flat. The effect on the indoor air temperature cannot be established from this data as the room in question is not thermally isolated from the rest of the building where the radiators are used as another heat source. The difference between the wall inner surface temperature $T_{wall,in}$ and the indoor air temperature T_{in}, however, can give a clearer indication of the effect of the thermal activation on the indoor conditions as the effect of the radiators in the rest of the building will be negligible on the temperature of the measuring point of $T_{wall,in}$.

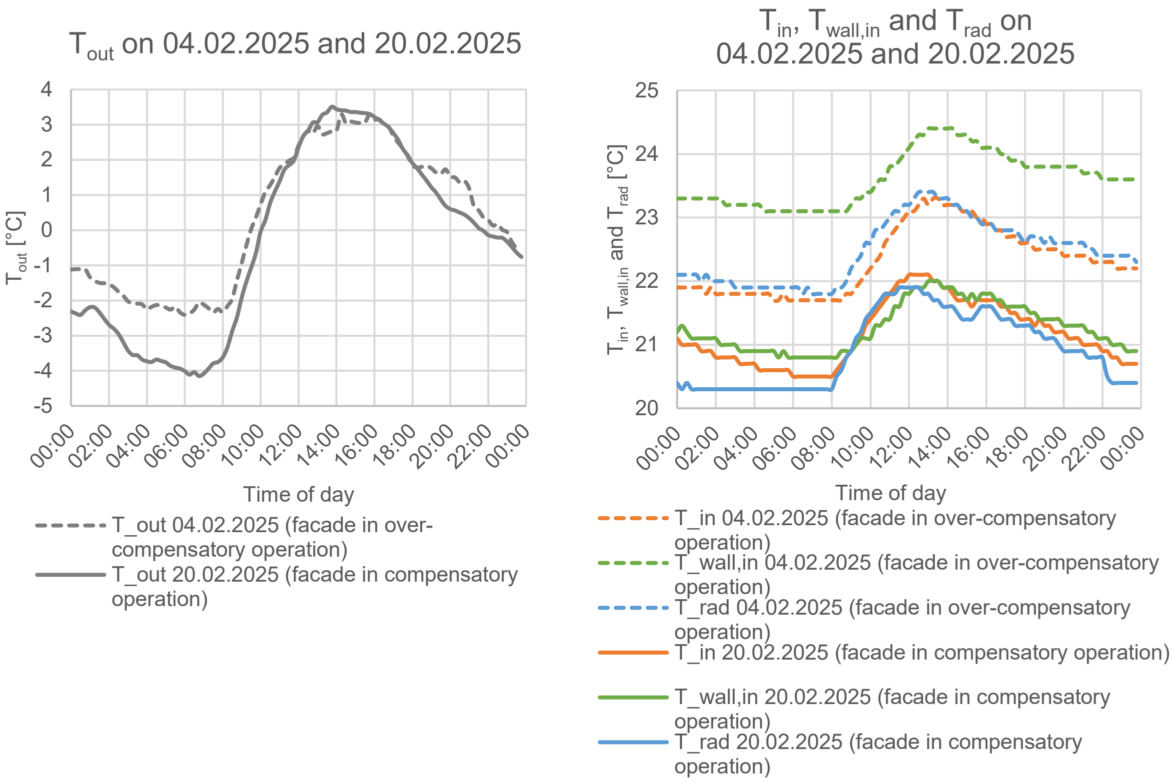

Figure 7. Comparison of the indoor and outdoor temperature levels for a day with the façade activation in over-compensators operation (04.02.2025) and a day with the façade activation in merely compensatory operation (20.02.2025).

3.2. Heat flow analysis based on temperature measurements

To describe the thermal behaviour of the façade activation and evaluate the amount of heat released to the building in relation to that lost to the environment, the heat fluxes originating from the façade activation were calculated based on measured temperature data of the façade as well as the indoor and outdoor air. Figure 8 shows the calculated heat fluxes for the activated façade area for the period of 23rd-31st January 2025. The outdoor air temperature in the observed time period fluctuated between approximately -2 and +13 °C and the indoor air temperature between 21 and 24 °C. The mean system temperature of the façade heating was relatively constant at approximately 31 °C. The resulting heat fluxes amount to between 4 and 6 kW for the heat flux directed to the inside of the building $\dot{Q}_{facade,in}$ and to between 2.5 and 4.5 kW for the heat flux directed towards the outdoor environment $\dot{Q}_{facade,out}$. This corresponds to a specific heat flux of between 7 and 10.5 W/m^2_{facade} for $\dot{q}_{facade,in}$ and to between 4.4 and 7.9 W/m^2_{facade} for $\dot{q}_{facade,out}$. The total heat flux originating from the façade activation therefore amounted to up to 10 kW or 17.5 W/m^2_{facade}. It should be noted that here also, the used indoor air temperature originates from one flat and is assumed to prevail in the entire building. Similarly, the flow and return temperature of the façade activation were assumed to be those of the manifold supplying the heating circuits on the street side of the building, since temperature data for the courtyard side of the building was not available. However, all façade heating circuits are operated at the same flow temperature, making this a plausible assumption for the flow temperature of all heating circuits. Groß and Schmidt [9] conducted a heat flow analysis for various flow temperature levels and U-values of the existing wall to obtain $\dot{q}_{facade,in}$ and report a value of 9.7 W/m$^2_{\text{facade}}$ for a flow temperature of 31 °C and a U_{in} of 1 W/m^{2}K. This is higher than the heat flux observed in this study and is due to the fact that Groß and Schmidt work with capillary mats with a pipe gap of 2 cm rather than 30 cm. Hinterseer et al. [10] studied a retrofitted thermal activation on an existing wall with a U_{in} of 1.4 W/m^{2}K and a thermal activation pipe gap of 20-25 cm operating at a flow temperature of 32 °C and resulting in a $\dot{q}_{facade,in}$ of approximately 17.1 W/m^{2}K. This shows the considerable impact of the U-value of the inner wall layers on the amount of heat transmitted to the indoor environment, even at more similar pipe spacings.

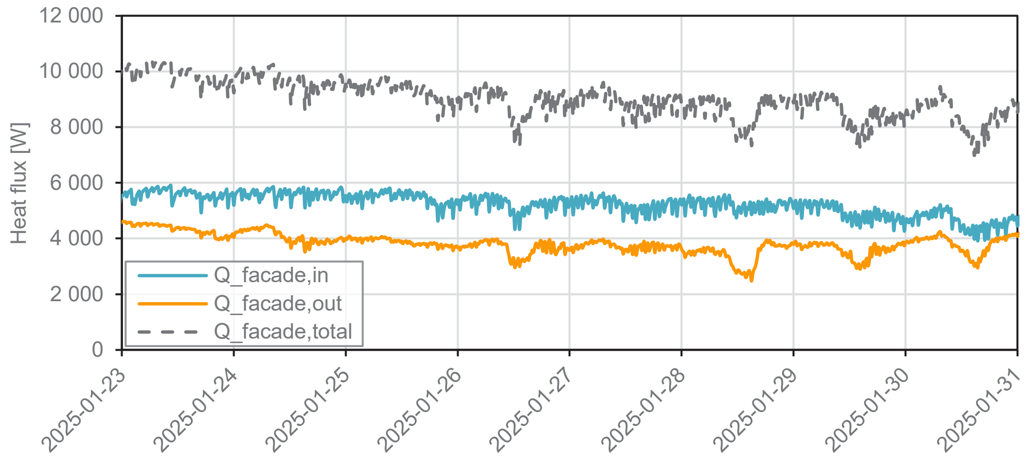

Figure 8. Calculated heat fluxes to the inside ($\dot{Q}_{facade,in}$) and outside environment ($\dot{Q}_{facade,out}$) for the period of 23rd – 31st January 2025.

3.3. Amount of heat transferred based on temperature measurements and heat meter data

Based on the heat fluxes $\dot{Q}_{facade,in}$ and $\dot{Q}_{facade,out}$, the amount of heat transferred can be calculated and aggregated to give the total amount of heat transferred during a specified time period. Alternatively, the monitoring system in the test case building comprises heat meters at various points in the system. Heat meter readings exist for 6th December 2024 until 25th March 2025 (the period during which the façade activation was in operation for the heating season). Table 1 shows the total amount of heat transferred at various measuring points for the heating season 2024/25 and also puts them into relation with the façade and conditioned floor area. It should be taken into account that the given values refer to the total amount of heat transferred and that part of it is lost to the environment as $Q_{facade,out}$.

Table 1. Measured amount of heat for the period of 6th December 2024 – 25th March 2025 for various measuring points and their corresponding values in relation to the facade area and the conditioned floor area, respectively.

Measuring point	Value	Unit
Measured heat from façade circuits manifold to courtyard side circuits	3,040.0	kWh
Measured heat from façade circuits manifold to street side circuits	10,150.0	kWh
Measured heat from buffer tank to façade circuits manifold	13,207.0	kWh
Measured heat from heat pumps to buffer tank	13,543.0	kWh
Measured heat from façade circuits manifold to courtyard side circuits	25.4	kWh/m$^2_{\text{facade}}$
Measured heat from façade circuits manifold to street side circuits	22.5	kWh/m$^2_{\text{facade}}$
Measured heat from buffer tank to façade circuits manifold	13.2	kWh/m$^2_{\text{cond. floor}}$

The reading intervals of the heat meters amount to between 2 weeks and 1 month. The data from the heat meters can be used to roughly cross-validate the heat flux calculation results given above. For this, a time period corresponding to a reading interval of the heat meters with full availability of temperature measurement data was selected, this being 22nd January until 4th February 2025. For this period, the measured amount of heat is 3,087 kWh and the calculated amount of transferred heat $Q_{facade,total}$ amounts to 2,841 kWh corresponding to a deviation of 8 % from the heat meter measurements. Taking heat losses between the measurement point of the heat meter and the façade activation (connecting pipes) into account, this deviation is considered acceptable.

3.4. Thermal power and heat production of the heat pumps based on the electrical power used

The electrical power consumption of the air-to-water heat pumps supplying the façade activation was recorded and multiplied by an assumed stationary COP taken from the heat pumps' data sheet to obtain an approximation of the thermal power $\dot{Q}_{th,i,j}$ (Power1 and Power2 in Figure 9) as well as the heat output $Q_{th,i,total}$ (Heat1 and Heat2 in Figure 9) of the heat pumps. The observation period lasted from 2nd December 2024 until 17th March 2025 with a logging gap between 6th and 17th December 2024 due to technical problems of the electrical power measurement devices. During this time period, heat pump 1 produced 4,878 kWh of heat and heat pump 2 produced 5,687 kWh.

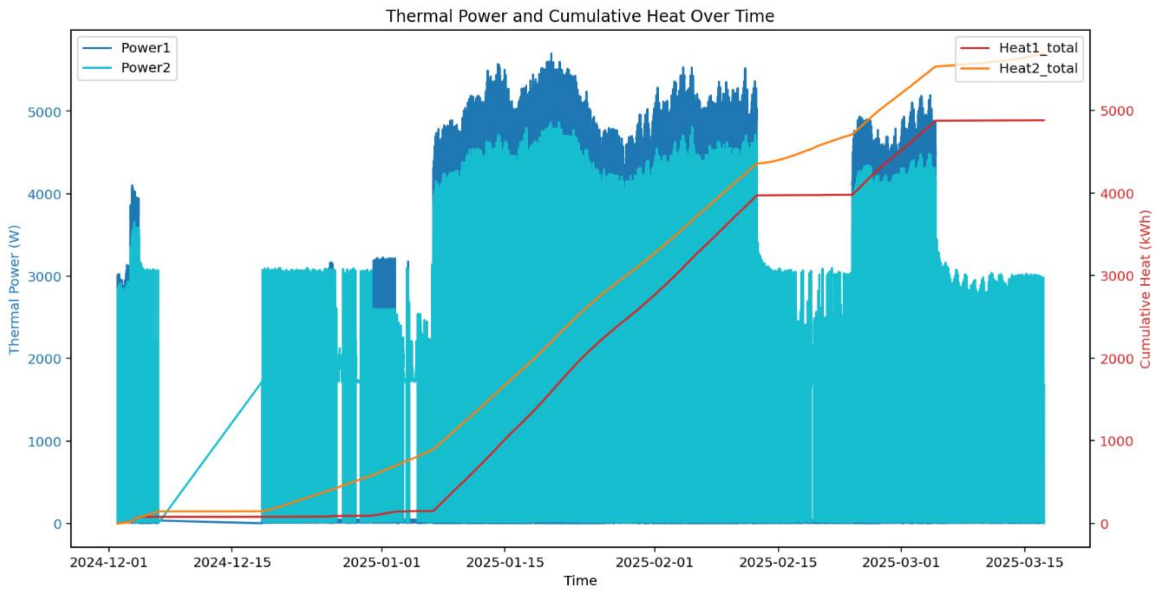

Figure 9. The thermal power and heat output for heat pump 1 (Power1 and Heat1_total) and heat pump 2 (Power2 and Heat2_total) for the observation period of 2nd December 2024 until 17th March 2025.

Aggregating this data, a maximum total thermal power $\dot{Q}_{th,total,j}$ of approximately 11 kW was observed as well as a total heat production $Q_{th,total}$ of 10,565 kWh.

Comparing $Q_{th,total}$ to the heat meter reading for the measuring point between heat pumps and buffer tank of 13,543 kWh for the observation period from 6th December 2024 to 25th March 2025, the calculated amount of heat seems plausible at first glance. However, a more detailed analysis taking the variation of the COP depending on the heat source (outdoor air) temperature as well as the observation gaps in the electrical power measurements into account would allow a more reliable cross-validation. This is planned to be conducted in the course of future data analysis work in the research project. Based on the electrical power data and the heat meter data, a SPF can be calculated for a defined period. For this, the heat meter reading interval of 10th January until 4th February 2025 with full availability of electrical power data was chosen. During this period, the outdoor air temperature fluctuated between -3 and +13 °C and the heating water flow temperature amounted to 35 °C. The electricity consumption of the heat pumps $E_{el,total}$ amounted to 1,437 kWh and the metered heat at the measuring point between heat pumps and buffer tank to 5,657 kWh, resulting in a SPF of

3.9. For future research, a quantification of emissions based on monitoring data in comparison to the state before refurbishment is of interest to determine the climate impact of the measures implemented.

4. Conclusions

In conclusion, the evaluations show that the thermal façade activation has indeed an effect on indoor conditions as the façade's inner surface temperature is higher for over-compensatory operation, resulting in a heat flux from the façade into the indoor environment as well as higher resident comfort. The heat flow analysis shows that during over-compensatory operation, the heat flux directed to the inside of the building is larger than that directed to the outside and that the maximum total thermal power of the thermal activation amounts to 17.5 W/m^2_{facade} for the chosen observation period with a mean system temperature of the thermal activation of 31 °C. Of this, the maximum useful heat flux directed to the indoor environment was 10.5 W/m^2_{facade}. The total amount of heat released via the façade activation during the heating period of 2024/25 was established as 13,190 kWh or 22.5-25.4 kWh/m^2_{facade} via heat meter measurements. First comparisons to the calculated heat production of the heat pumps from electrical power measurement data shows no contradiction, but still needs further refining due to gaps in the measurement data. Finally, the SPF was calculated for the sample period of 10th January – 4th February 2025 amounting to 3.9 which may be deemed an acceptable value for air-to-water heat pumps.

Nomenclature

Symbol	Description	Symbol	Description
Latin characters		$Q_{th,total}$ [kWh]	total heat released by all heat pumps
A_{facade} [m^2]	façade area	$\dot{Q}_{th,total,j}$ [W]	total thermal power of all heat pumps at time step j
COP [-]	coefficient of performance	SPF [-]	seasonal performance factor
$E_{el,i,j}$ [kWh]	electricity consumption per heat pump i and time step j	$\bar{T}_{facade}$ [°C]	mean façade core temperature
$E_{el,i,total}$ [kWh]	total electricity consumption per heat pump i	$T_{facade,i}$ [°C]	temperature of façade sensor i
$E_{el,total}$ [kWh]	total electricity consumption of all heat pumps	$T_{flow,GrNeu}$ [°C]	flow temperature at manifold feeding the street side heating circuits
$P_{el,i,j}$ [W]	electrical power per heat pump i and time step j	T_{in} [°C]	indoor air temperature
$\dot{Q}_{facade,in}$ [W]	total heat flux from façade to indoor environment	T_{out} [°C]	outdoor air temperature
$\dot{q}_{facade,in}$ [W/m^2_{facade}]	specific heat flux from façade to indoor environment	T_{rad} [°C]	radiator surface temperature
$Q_{facade,out}$ [kWh]	heat transmitted from façade to outdoor environment	$T_{return,GrNeu}$ [°C]	return temperature at manifold feeding the street side heating circuits
$\dot{Q}_{facade,out}$ [W]	total heat flux from façade to outdoor environment	$\bar{T}_{sys}$ [°C]	mean system temperature of façade activation
$\dot{q}_{facade,out}$ [W/m^2_{facade}]	specific heat flux from façade to outdoor environment	$T_{wall,in}$ [°C]	façade inner surface temperature
$Q_{facade,total}$ [kWh]	total heat transmitted by façade	U_{in} [W/m^{2}K]	U-value of wall layers between indoor air and façade activation
$\dot{Q}_{facade,total}$ [W]	total heat flux transmitted by façade	U_{out} [W/m^{2}K]	U-value of wall layers between outdoor air and façade activation
$Q_{th,i,j}$ [kWh]	heat released by heat pump i in time step j	**Greek characters**	
$\dot{Q}_{th,i,j}$ [W]	thermal power of heat pump i in time step j	Δt [s]	time step
$Q_{th,i,total}$ [kWh]	total heat released by heat pump i		

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