Renovation of a Multi-family-house with External Wall Heating System

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Abstract

A new and cost-effective heating concept integrated in a prefabricated façade for renovation of multi-family-houses was investigated in the framework of the European project PLURAL with the help of dynamic building and system simulations. The concept consists of a prefabricated insulated timber-frame façade containing the heating pipes of a low temperature hydronic distribution system for space heating. After renovation, the building can be heated with these heating pipes through the existing external walls. The simulation results show that such a system can ensure good thermal comfort for the flats and fulfill Nearly Zero Energy Building requirements. An optimized control strategy of the heating system allows to increase the photovoltaic self-consumption and to decrease the net costs for electricity of the building. Under certain conditions, such a system is a beneficial solution for fast and cost-effective renovation of multi-family-houses.

Keywords: renovation of multi-family-houses, external wall heating, prefabricated façade, NZEB, PV self-consumption

1. Introduction and motivation

In the European Union, the building sector is responsible for 40% of the final energy consumption (European Commission, 2021). An important challenge for the building sector concerns the energetic renovation of existing buildings (European Commission, 2016). Currently, the refurbishment rate of existing buildings is below 1% (European Commission, 2021) and, for this reason, it is crucial to overcome obstacles of renovation processes (e.g., high amount of time and investment cost, reallocation of the building's inhabitants, loss of rent, etc.) in order to achieve faster the goals of the energy transition in this sector.

Within the European project PLURAL (PLURAL, 2020), innovative "Plug-and-Use" kits for fast and energy efficient retrofitting are developed to meet Nearly Zero Energy Building (NZEB) targets, but also to ensure minimum disturbance of the inhabitants during the retrofitting phase.

The so-called Conductive External Wall (ConExWall) heating system is one of the solutions developed within the project PLURAL for energy retrofitting, in particular for multi-family houses (MFH). Such a system can be mounted directly on the existing outer walls of a building, providing energy for heating and cooling via a heating layer, thermal insulation, ventilation and, optionally, electricity by means of a photovoltaic (PV) system installed on the façade. Time and cost reduction for retrofitting, versatility, high potential of self-sufficiency, and integration with low temperature heating systems (e.g., heat pumps), make this system ideal for renovating MFHs with the goal of low specific energy demand and conversion from fossil fuels to energy systems with a high share of renewable energy.

2. ConExWall system

The operation principles of the proposed external wall heating concept without prefabrication were suggested and analyzed earlier by Luther et al. (2002) and limits and potential of such a concept were studied within different projects (Schmidt, 2018). Such a system allows the renovation of buildings "from outside" and this represents one of its biggest advantages, since the inhabitants are not forced to leave the building during the renovation period. Another big advantage of this heating concept is the thermal activation of the whole existing façade because the heating layer heats the rooms through the façade. This characteristic allows for using the existing wall as thermal storage. In case of a heating system with heat pump and PV, this enables to run the heat pump longer and to higher temperatures during times of excess electricity gains from the PV system and, on the other hand, to run it shorter during times were electricity has to be purchased from the electric grid.

Such a system presents, on the other side, some disadvantages and a crucial issue is that the potential heating

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energy delivered to a room is strongly dependent on the opaque external wall area. This aspect is important because some rooms (e.g. with higher window ratio) could become critical with regard to the thermal comfort. In addition, this system has to be supported by a different heat distribution system in case of internal rooms without external wall area (e.g., the bathroom).

The proposed ConExWall module (see Fig. 1) represents an evolution of the original concept because of two aspects: 1) the heating system is enclosed in a prefabricated timber-based module and 2) the module can be equipped with optional components for ventilation and renewable electricity production. The ConExWall module consists of:

- Timber frame construction with insulation of about 20-30 cm (depending on climate);
- Low temperature external wall heat (and optionally cold) emission system;
- Module-integrated windows with mechanical ventilation system including heat recovery (MVHR) integrated in the frame of the windows or in the new façade;
- Building integrated photovoltaic (BIPV) modules for electricity production.

The feasibility of such a system without extensive prefabrication was already demonstrated by means of a prototype test and simulations within a Swiss project (ProsumerSkin, 2017) where a first MFH located in Bern (Switzerland) has been renovated with this concept.

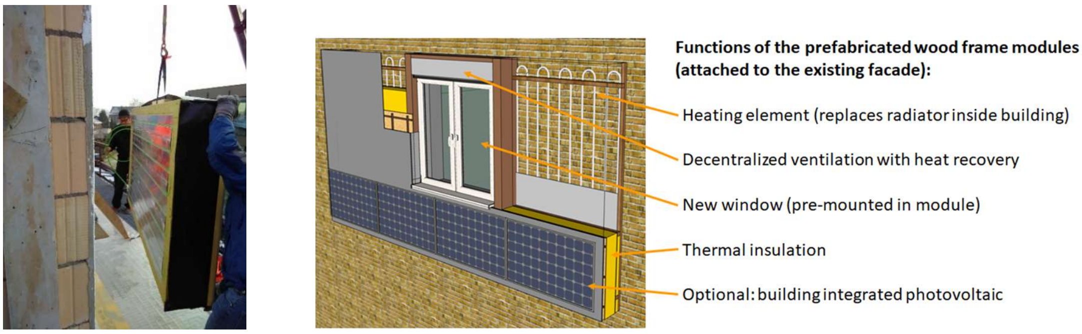


Fig. 1: Mounting of the prefabricated ConExWall on the façade test box (left) and concept visualization of the ConExWall solution (right).

3. Building and system simulation

3.1 Building

In the framework of the project PLURAL, the ConExWall concept will be installed for the renovation of a double dwelling (see Fig. 2) located in Kasava, Czech Republic. The existing building has an Energy Reference Area (ERA) of 196 m^2 and matches to the proposed ConExWall concept because of the high U-value (1.3 W m^{-2} K^{-1}) of the existing walls that allows for a good heat transmission between the ConExWall module and the building through the existing walls.

As detailed information about user behavior is not available (e.g., set point temperature, internal gains, ventilation and infiltration rates, etc.), the existing building was simulated in its pre-renovation state assuming standard boundary conditions. Simulation results showed an annual heating demand (with a set point temperature of 20 °C) of 163 kWh m^{-2}_{ERA} a^{-1}. Simulation results of the building before renovation were validated against real energy consumption, showing a good match (relative deviation of 7%).

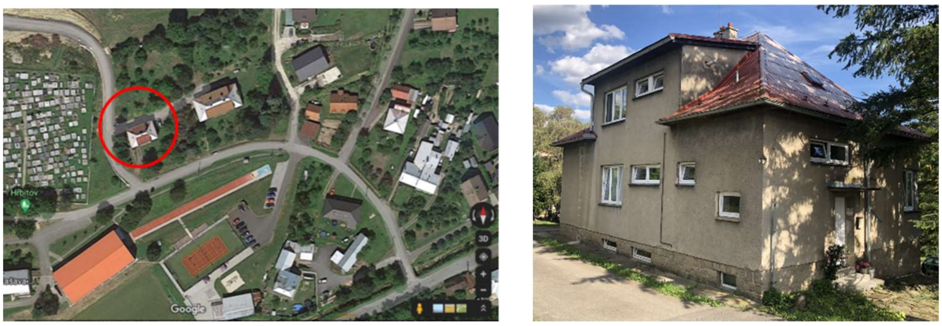


Fig. 2: Location of the building under study (left) and view of the existing building (right).

3.2 Building model and boundary conditions

In order to study the energetic performance of the ConExWall and the thermal comfort of the renovated building, a building model (see Fig. 3) was generated (SketchUp, 2022) and then imported into the simulation tool (i.e. through the use of TRNSYS-Type 56), where the complete heating system was modelled in order to perform the building and heating system simulation (TRNSYS, 2022).

The renovated building (with an ERA of 275 m^2) consists of a cellar (modelled as a single thermal zone) and two floors (i.e. two apartments), with an internal staircase. In order to study the thermal comfort of each room of the building in detail, each room was modelled as a single thermal zone. In total, 17 thermal zones are simulated. Each of the two flats consists of a corridor ("Hall"), a bathroom ("Bath"), a restroom ("Rest"), one kitchen/living room ("Liv") and two resp. three sleeping rooms ("Bed") (see Fig. 5). Each flat has also an external unheated storage room next to the staircase. More living area through a new and higher roof will be created in the first floor with the renovation.

Tab. 1 summarizes the wall and window constructions of the building after renovation. In the table the construction "External wall" represents the existing wall (i.e. the wall on which the ConExWall will be placed) after renovation, while "External $wall_{new}$" represents the new external wall of the first floor that will be necessary in order to extend the second flat. The building will be equipped with triple panes window (filled with Argon) with internal Venetian blinds between two of the panes. Reference shading control strategies were considered for the simulation based on the total irradiation on the window surface and convective temperature of the room.

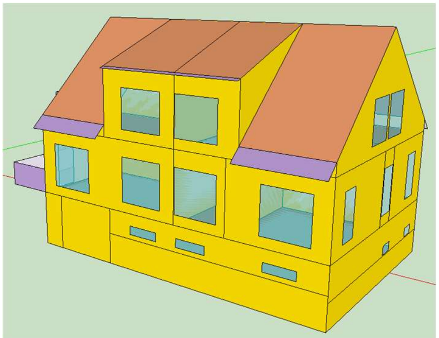


Fig. 3: 3D model in SketchUp of the same building after renovation.

Tab. 1: U- value of wall and window constructions of the building after renovation

Wall / Window construction	U [W m^{-2} K^{-1}]	Note
Basement floor/wall/ceiling	3.43/1.31/0.30	basement ceiling insul. with PUR
Internal ceiling/wall	0.82/2.65	
Internal wall of staircase	0.34	insulated with EPS
Roof	0.10	
External wall	0.13	
External $wall_{new}$	0.14	new ext. walls of the first floor
Window	0.60	frame ratio of 0.2, g = 0.49

In the building model, internal gains due to people, lighting, and appliances were considered. Since hourly profiles for occupancy are not available in the Czech national regulations, standard occupancy profile from Swiss norm SIA 2024 (SIA, 2022) was assumed. A specific internal gain due to people (P) of 2.0 W m^{-2} and humidity source of 80 g h^{-1} P^{-1} were considered. Benchmark numbers of the latest study of Czech Statistical Office (CSU, 2017) show a specific electricity consumption (for lighting, appliances, cooking and other) of 28.6 kWh m^{-2} a^{-1} for dwellings in Single Family House (SFH). To reach this electricity consumption, a specific internal gain (for equipment and lighting) of 5.5 W m^{-2} was set, assuming a typical electric power profile processed statistically by the Czech energy market operator. Internal gains inside staircase, cellar and storage rooms were set to zero.

Fixed infiltration rate of 0.15 $m^3\ h^{-1}\ m^{-2}$ was assumed for all rooms, according to the Swiss norm SIA 2024.

3.3 ConExWall in TRNSYS – Active layer in Type 56

As described in previous sections, the simulation study is performed with the simulation tool TRNSYS and, in particular, "Type 56" is used in order to model the building. Within the Type 56, to model the ConExWall, the sub-model "active layer" was used. This active layer model can be added to a wall, floor, or ceiling in order to model a radiant heating or cooling system. The layer is called "active" because it contains fluid filled pipes that add or remove heat from the building component. For the definition of the "active layer" of the ConExWall in Type 56, distance between the heating pipes was set to 0.13 m and a pipe wall conductivity of 0.4 $W\ m^{-1}\ K^{-1}$ was assumed. Pipe outside diameter and pipe wall thickness were set to 0.014 m and 0.002 m, respectively. As it is important to take into account possible imperfections in the thermal coupling of the ConExWall modules to the old façade due to surface roughness, an air gap of 2 mm was assumed in the model between the "active layer" and the existing wall. This air gap reduces the heat transfer from the external wall heating system into the building.

3.4 HVAC system and control strategy

Fig. 4 shows the layout of the heating and domestic hot water (DHW) system. An air to water heat pump (AWHP) with a nominal heating capacity of 11.3 kW is used for space heating (SH) and DHW preparation. A combi thermal energy storage (TES) with 750 l water volume is considered in order to store heat produced by the heat pump (HP). In the SH demand side of the system, each ConExWall was modelled as a separate heating loop (i.e. all the loops are in parallel and with the same supply temperature) and is equipped with a circulation pump in order to control the mass flow rate of each heating loop independently. When realized, the ConExWall loops will be equipped with control valves instead and a central recirculation pump will control the mass flow of the heating water.

Fig. 5 shows the layout of the heat emission system of the building. As described in previous sections, the ConExWall represents the main heating system and almost all the rooms of the building are heated through this concept (see Tab. 2). Since new walls will be built on the first floor, the children room and part of the living room of the first floor will be heated through a standard heating wall system (see orange elements in Fig. 5) located at the inside of the respective walls. Cellar, staircase, and storage rooms are not heated, while electric radiators are considered in the two bathrooms for comfort reasons.

As described, the AWHP will cover the SH as well as the DHW demand. As measurement data of the building for DHW consumption are not available, reference DHW load profiles for SFH were used (IEA SHC Task44). In order to take into account the presence of two apartments, a scale factor of two was assumed for a total energy demand for DHW preparation for the whole building of 4266 $kWh\ a^{-1}$.

Within the renovation process of the building, decentralized ventilation units integrated in the walls or in the window frame will be installed. In the building model, the cellar, staircase, halls, and storage rooms are not actively ventilated, while the other rooms are equipped with decentralized ventilation units with energy recovery (i.e., heat and humidity). Constant heat recovery (70%) and humidity efficiency (56%) is assumed for the ventilation unit with a control of the airflow rate through step variation as function of the room relative humidity (airflow rate between 10 and 85 $m^3\ h^{-1}$ for each ventilation unit). Summer night cooling (i.e., by-pass of heat recovery) is implemented in the model based on the ambient temperature and on the room temperature.

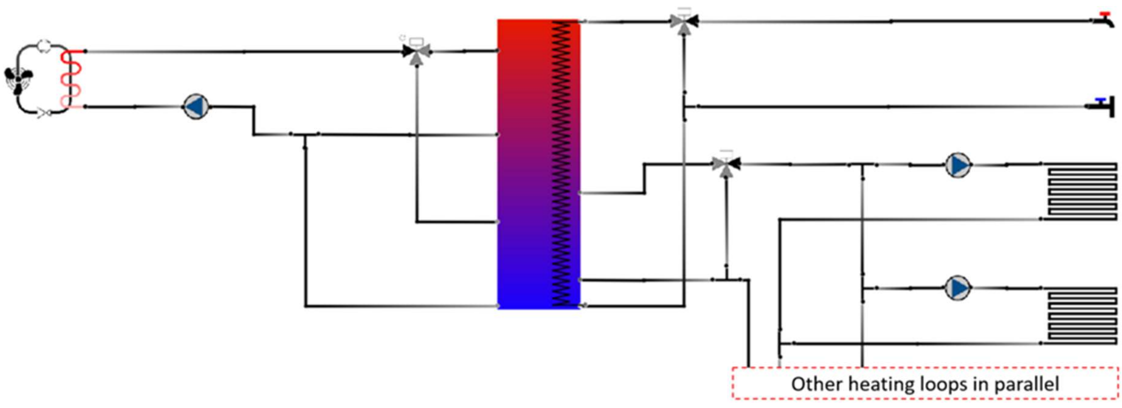


Fig. 4: Layout of the system for space heating and DHW preparation.

Fig. 5: Layout of the heating surfaces of the ground floor (Gf) and first floor (1f) of the building - ConExWall (red), electric radiator (yellow) ad internal wall heating (orange).

Tab. 2: Window ratio (Window area / External wall area) and net heated wall area for all rooms of the building.

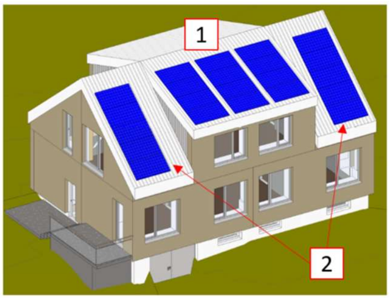
Zone	Window ratio [%]	Net heated wall area [m^2]
GfRest	0	6.1
GfHall	21	10.7
GfBath	15	8.0
GfBedN	5	24.4
GfLiv	23	30.1
GfBedS	40	4.6
GfBedE	17	24.3
1fRest	0	3.0
1fHall	19	5.4
1fBath	12	9.3
1fLiv	31	16.7
1fBedS	32	6.1
1fBedE	23	19.7

The reference control strategy of the system is based on "standard" control for the activation of the HP for space heating and DHW preparation. The thermal storage is equipped with four temperature sensors (two sensors in the DHW volume and two sensors in the SH volume) with which the HP is activated to keep the TES volumes to the desired temperatures. In particular, a set point temperature of 50 °C is used for DHW preparation, while for space heating a heating curve as linear function of the average ambient temperature (i.e. supply water temperature of 35 °C at -10 °C and 24 °C at 14 °C) is used. The heat pump gives priority to the DHW preparation (with respect to the SH), while the heating season is defined based on the ambient temperature ($Tamb_{48h}$ < 15 °C). Each circulation pump is activated depending on the room temperature in order to keep a convective temperature of 21 °C in each heated room. Modulation of compressor power or optimization strategies of PV self-consumption are not considered in the reference control strategy.

3.5 PV system

Fig. 6 shows the layout of the PV system that will be installed on the roof of the building during the renovation process. Only the part of the roof oriented to the south (i.e. 16° S-E) will be covered with PV panels for a total photovoltaic surface of approximately 48 m^2 (9.9 kW_p). Each PV subfield will be equipped with an inverter and the system will be connected to the grid.

In the building model, the PV electricity is used firstly to cover the electricity demand for households and ventilation and then, if PV is still available, to cover the electricity demand of the HP (i.e. heating and DHW preparation).



	PV Field 1	PV Field 2
Inclination	20°	40°
Number of PV modules	12	10
PV surface [m^2]	26.1	21.7
PV power [kW_p]	5.4	4.5

Fig. 6: Layout of PV system (left) and information about the two PV subfields (right).

4. Simulation results and discussion

4.1 Overview of the simulation study

The simulation study was performed with the pytrnsys package (Pytrnsys, 2022), a complete python-based framework for TRNSYS simulations developed at the SPF Institute for Solar Technology at the Eastern University of Applied Sciences (OST). Pytrnsys provides a framework to build, simulate, post-process, plot and report TRNSYS simulations. It is designed to give users an extensively automatized way to execute and share building and system simulations performed with TRNSYS.

Energy consumption of the system and thermal comfort of the building was investigated. The simulation study was performed with the reference control strategy (see 3.4) and an optimized control strategy was tested (see 4.4) in order to study the influence on the PV self-consumption and net costs for electricity.

A whole year was simulated considering a time step of five minutes. Climate data from Meteonorm for the location of Kasava (CZ) was used. A set point temperature for the building of 21 °C was considered.

4.2 Energy

Fig. 7 to Fig. 9 show the main simulation results concerning the heating and electricity balance for the whole system. A total space heating demand of 4542 kWh a^{-1} was calculated (i.e. 16.5 kWh m^2_{ERA} a^{-1}) for the whole building. In the summer period from June to September, the HP works only to cover the DHW demand (Fig. 7). 21% of the heating energy delivered by the HP is lost (through HP, pipes and TES).

On the electrical side, Fig. 8 shows that most of the self-consumed electricity from PV (approx. 93%) is used for building demand (i.e., light, equipment and ventilation) and only a small part is used by the HP. A total annual PV production (after inverter) of 11'187 kWh was calculated with a PV self-consumption quota (i.e. PV_{self} / PV) of 30%. Fig. 9 shows that most of the electricity demand of the building is covered by electricity from the grid with an annual grade of autarky (PV_{self} / El_{tot}) of 31%. The HP causes 25% of the total electricity demand of the building.

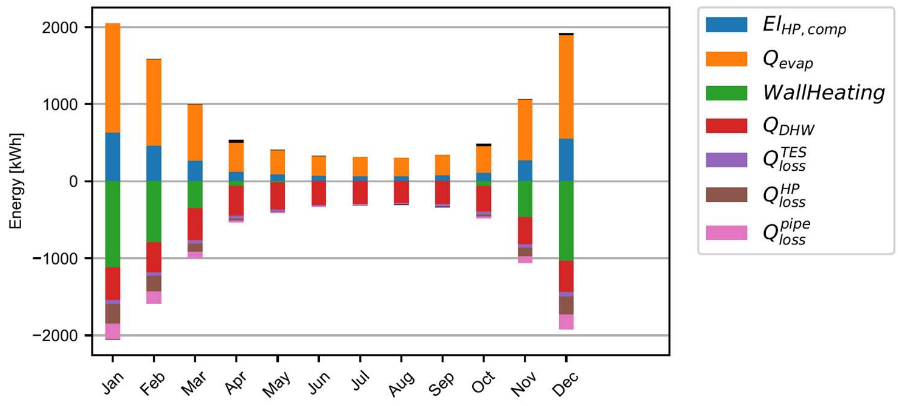


Fig. 7: Monthly heating balance of the system - heat delivered by the heat pump is used to cover heating demand of building ("WallHeating") and DHW.

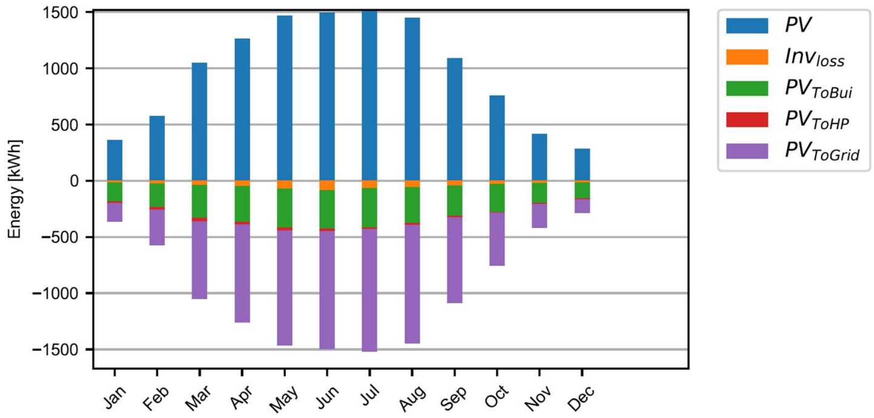


Fig. 8: Monthly balance of PV electricity - "PV_{ToBui}" represents the PV electricity self-consumed by the building (i.e. for households and ventilation), "PV_{ToHP}" represents the PV electricity self-consumed by the HP.

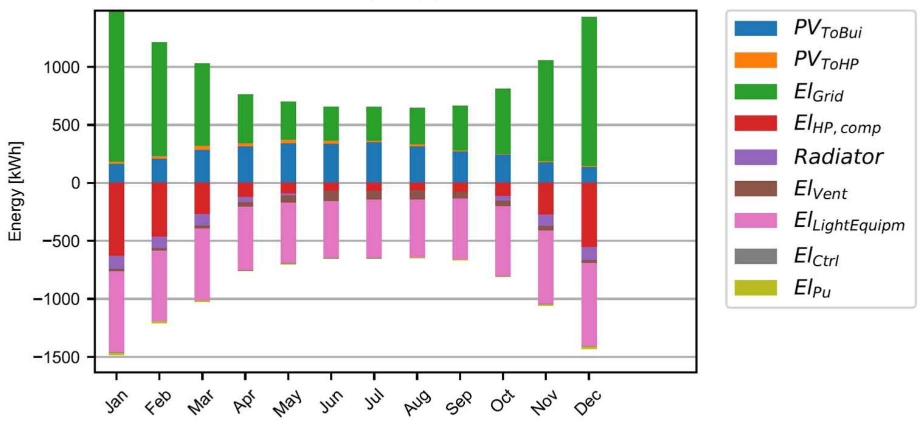


Fig. 9: Monthly electricity balance of the system.

The general behavior of the system for a week during the heating season is given in Fig. 10. It is interesting to note that the heating concept ConExWall is able to keep 21 °C in the room "GfBedN", but the actual reference control strategy leads the heat pump to work especially during the nighttime, when PV electricity is not available and all the electricity demand of the compressor of the heat pump must be purchased from the grid. The plot shows also that there is a good potential to increase PV self-consumption through a control of compressor speed. This strategy could make the heating cycle longer by means of reducing the compressor power in order to avoid peaks in electricity demand and, as consequence, match the actual PV electricity.

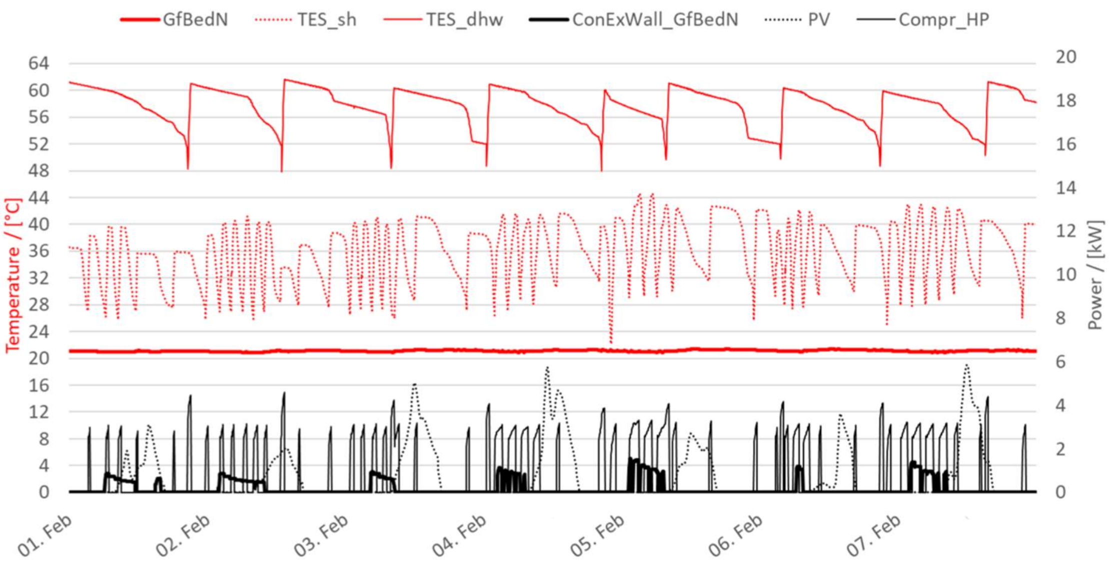


Fig. 10: Behavior of the system for a week during the wintertime. "ConExWall_GfBedN" represents the heating energy delivered to the room (i.e. GfBedN). Temperature in the thermal storage of the two volumes (space heating and domestic hot water) is given.

The building under investigation will be renovated with the goal to achieve NZEB requirements. Simulation results were used to calculate the NZEB energy performance indicators (see Tab. 3) according to the national Czech laws (in particular the "Act. No 406/2000 Coll." and "Decree No. 264/2020 Coll."). The three indicators are defined as follows:

- U_{em} is the U value of the building weighted with the surfaces area;
- Q_{fuel} is the sum of the total electricity demand of the building and the extracted ambient energy from the evaporator of the HP;
- Q_{nPE} is the non-renewable primary energy (PE) demand of the building, assuming that the primary energy factors (f_{PE}) for purchased electricity, electricity to the grid and ambient energy are 2.6, -2.6 and 0, respectively.

Simulation results show that the renovation concept is able to fulfill the NZEB requirements. In particular, the non-renewable primary energy demand (i.e., Q_{nPE}) is negative because of the fact that, on annual basis, the amount of electricity fed into the grid is higher than the electricity purchased from the grid.

Tab. 3: NZEB analysis of the building with the proposed renovation concept.

Energy performance indicators	New building as NZEB (2022)	Simulation results	Fulfilled/Not fulfilled
U_{em} [W m^{-2} K^{-1}]	0.29	0.21	Fulfilled
Q_{fuel} [kWh a^{-1}]	34094	18531	Fulfilled
Q_{nPE} [kWh a^{-1}]	19383	-213	Fulfilled

4.3 Thermal comfort

The standard EN ISO 7730 was followed to define the thermal comfort zone, since there are no special regulations in Czech Republic regarding the definition of thermal comfort for dwellings. Fig. 11 shows the thermal comfort for three rooms of the building exemplarily. It is important to note that in this simulation study a cooling of the building during the summer season was not considered. The thermal comfort plots show that, in general, thermal discomfort during wintertime does not occur and the ConExWall system is able to heat the different rooms of the building sufficiently. If the two bedrooms of the ground floor (i.e., "GfBedS" and "GfBedN") are compared, it can be noted that the heating system is able to keep the set point temperature of 21 °C better in room "GfBedN" than in room "GfBedS". The reason is due to the larger heated surface of the first room compared to the latter one, which has only a small heated area and a large window. The living room of the first floor ("1fLiv") shows a good thermal comfort, even if overheating during the summer season occurs with a maximum operative temperature of 27.6 °C.

Fig. 12 gives an overview of the thermal comfort for the different rooms of the building when using the Predicted Mean Vote (PMV) factor defined in the standard norm ISO 7730 (ISO, 2022) regarding the thermal comfort for buildings. The norm recommends a PMV between -0.5 and 0.5 (in case of category B), but a small percentage of time (not defined in the norms) outside this interval is accepted in general. To calculate the PMV in Type 56 for the different rooms, a metabolic rate of 1.2 met and a clothing factor of 0.5 in summer and of 1 in winter was assumed. The plot shows that the PMV value goes below the limit of -0.5 for most of rooms of the ground floor. Despite this, detailed analysis of the PMV for the different rooms indicates that the number of hours for which PMV < -0.5 is below 4% for each of the rooms.

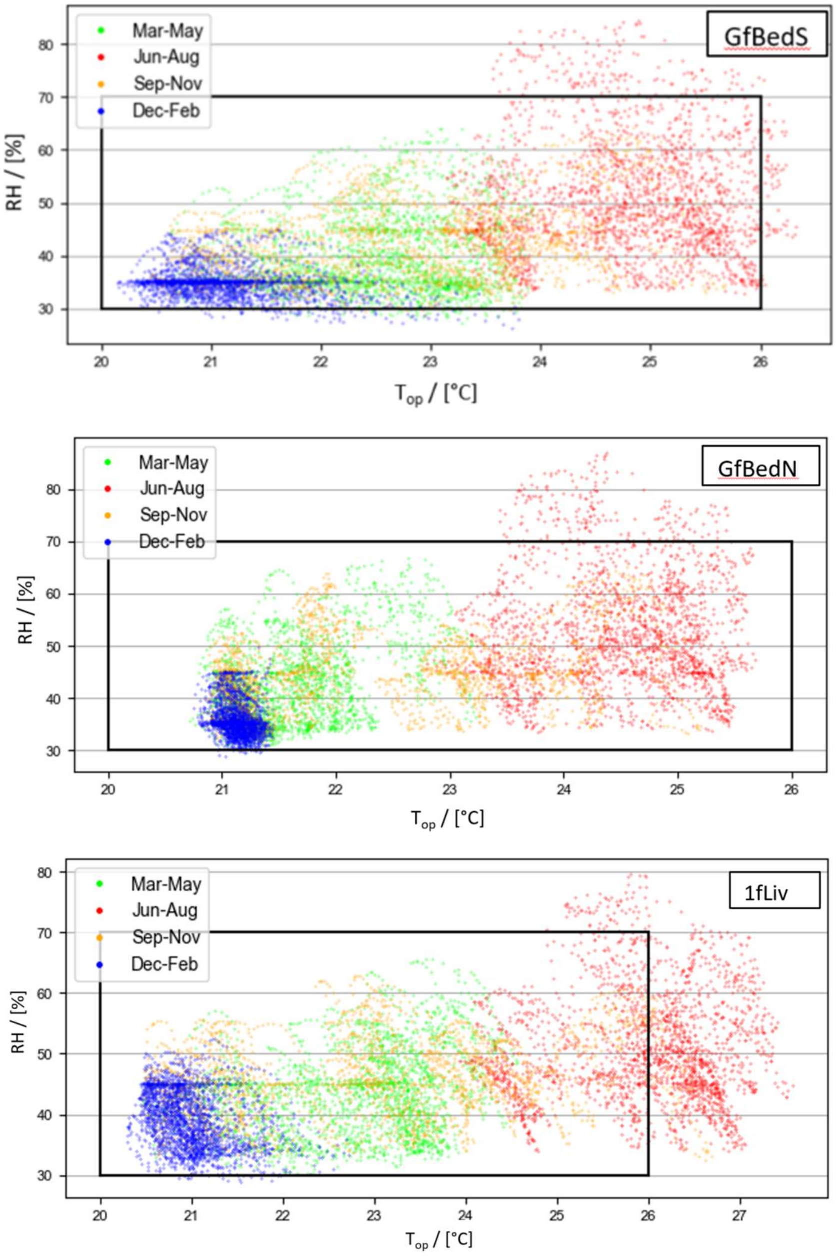


Fig. 11: Thermal comfort (relative humidity vs. operative temperature) for three different rooms of the building (names of the rooms: see Fig. 5). The colors indicate the seasons (see legend).

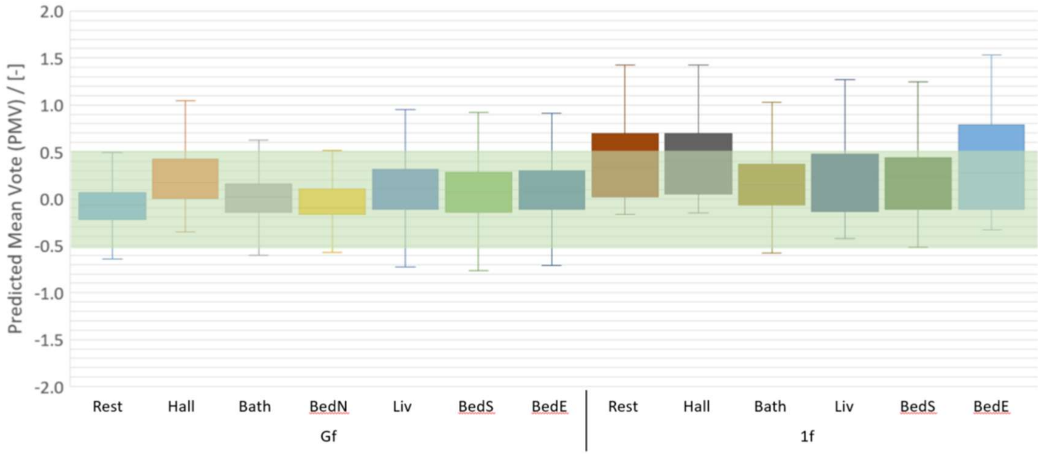


Fig. 12: Predicted Mean Vote (PMV) for the rooms of the building.

4.4 Control strategies – Optimization of PV self-consumption

As described in the previous sections, the standard control strategy neither includes a modulation of compressor speed of the HP nor a coordination between the HP and the PV production in order to increase the PV self-consumption.

To decrease the costs for electricity of the system, an optimized control strategy was implemented and tested (see Fig. 13). The approach is simple and is based on the overheating of the thermal storage (TES) and of the building (using its thermal mass) if PV electricity is still available after subtracting the electricity demand of the building. Through the modulation of the compressor power, remaining electricity coming from PV system (i.e., PV_{forHP}) and compressor power are equalized as much as possible in order to increase PV self-consumption, avoiding peaks in electricity demand for HP. On the other side, when PV electricity is not available for the HP, the control tries to reduce the heating demand of the whole system through the reduction of the set point temperature in the thermal storage and in the building. Following this approach, the goal was to move the heating cycles of the HP as much as possible to the daytime (where PV is available and outside temperature is higher) to decrease net costs of the system during operation phase and to increase the efficiency of the HP.

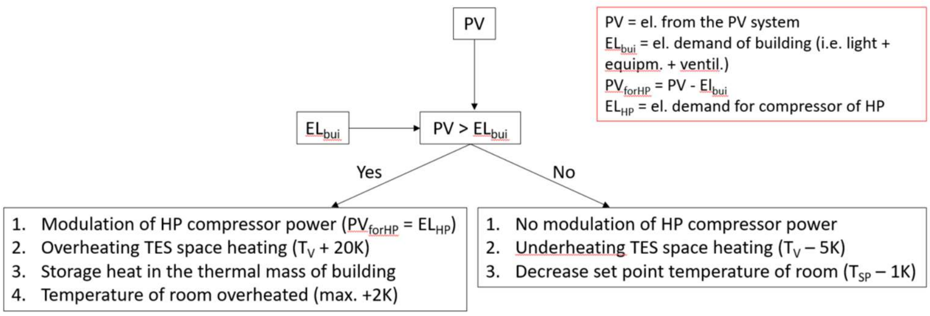


Fig. 13: Block diagram of the optimized control strategy.

Fig. 14 shows how the optimized control strategy works for a typical week during wintertime. It is immediately clear that the control strategy reduces strongly the number of heating cycles of the compressor of the heat pump ("Compr_HP") and, in the meantime, moves them to the day when PV is potentially available for the system ("PV_forHP"). Peaks are reduced and the modulation of compressor speed allows to increase PV self-consumption during the day when, in the meantime, heat is stored in the thermal mass of the building. Overheating of thermal storage is not visible here because of the fact that PV production (and as consequence potentially available for the heat pump) is small in comparison to warmer period like Apr – May.

Tab. 4 shows the comparison of the reference and the optimized control strategy on an annual basis. As expected, due to the fact that the thermal storage and the façade are overheated during the winter season, thermal losses of the storage are higher as well as the heating energy through the ConExWall. Because the heat pump works more during the day (i.e., higher evaporation temperature due to higher ambient temperature), the seasonal performance factor (SPF) of the heat pump is slightly increased (+10%). Tab. 4 shows also the comparison between the control strategies with regard to the electricity exchange with the grid and net costs (i.e., difference between costs for purchased electricity and profit from PV fed into the grid). The electricity exchange with the grid is decreased (good effect on grid stability) and the optimized control strategy allows to reduce the net costs for electricity of 20% (feed-in tariff for PV of 0.06 €/kWh and tariff for purchased electricity of 0.19 €/kWh were assumed). Considering the optimized control strategy, PV self-consumption is increased to 42% (from 30% of the reference control strategy) and the grade of autarky is increased to 43% (from 31% of the reference case).

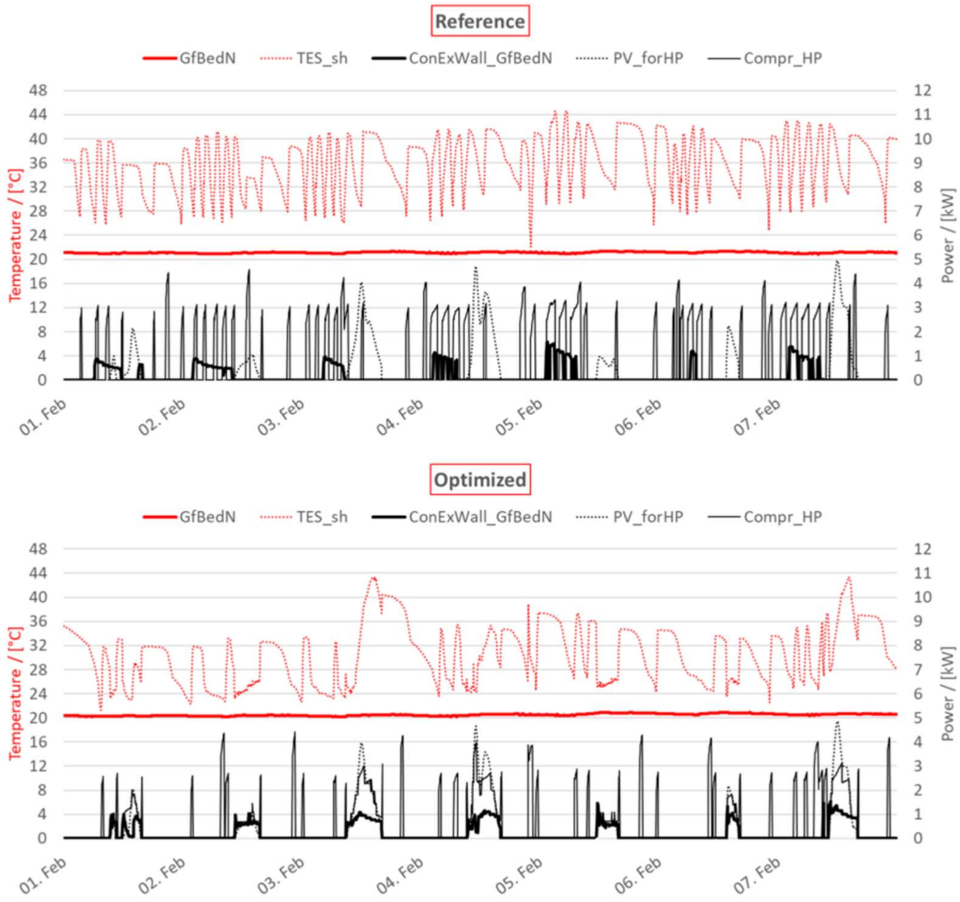


Fig. 14: Behavior of the system during a typical week of the heating season - Comparison between "Reference" and "Optimized" control strategy. "PV_forHP" represents the PV electricity available for the HP (PV electricity for households and ventilation already subtracted).

Tab. 4: General comparison of the reference and optimized control strategy - Feed-in tariff for PV: 0.06 €/kWh, tariff for purchased electricity: 0.19 €/kWh.

	Reference control strategy	**Optimized control strategy**	**Relative deviation [%]**
El. from grid [kWh a^{-1}]	7717	6265	-19%
PV to grid [kWh a^{-1}]	7799	6528	-16%
Net costs [€ a^{-1}]	998	799	-20%
TES_{loss} [kWh a^{-1}]	420	471	+12%
Heat of ConExWall [kWh a^{-1}]	3915	4411	+13%
SPF_{HP} [-]	3.3	3.6	+10%

5. Conclusions

The proposed ConExWall heating concept was investigated within the European project PLURAL through building and system simulations. The simulation results show that such a system is able to ensure good thermal comfort in all the rooms of the analyzed building (PMV < -0.5 for less than 4% of the time) and fulfill Czech NZEB energy requirements. The results show some possible critical issue for the rooms with high window ratio or small façade area available for heating. These particular rooms (e.g. the small bedrooms on the south side of the investigated building) might need an additional heat source (like a convector) or an increase of the heating curve in order to ensure good thermal comfort. Through an optimized control strategy of the system, PV self-consumption and grade of autarky are increased to 42% and 43% (from 30% and 31% of the reference case, respectively), while the net costs for electricity decrease by 20%. The ConExWall system can represent, under certain conditions, a valuable solution in case of renovation of multi-family-houses.

6. Acknowledgments

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