Reaching PEB with renovated building using Multi-functional façades

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ABSTRACT: As the building sector is very important to reach the EU energy savings goals, a directive was approved and named as EPBD 2010/31/EU in 2010. Another directive to boost the goals was approved in 2012 named Energy Efficiency Directive 2012/27/EU. Hence, this issue became more and more important both directives were then amended and covered within the Energy Performance of Buildings Directive 2018/844/EU, which includes new further elements and motivation to modernize the building sector mainly by means of increasing the building renovation rate. Therefore, the commission presented its renovation wave strategy as part of the European Green Deal in October 2020. In fact, according to the European Commission, the building sector holds about 40 % of the EU energy consumption and 35 % of the buildings are older than 50 years, where almost 75 % of the building stock is energy inefficient. Another statistic from the European Commission shows that the renovation rate is only about 1 % of those buildings. In Austria, the situation is similar to the abovementioned situation for the EU, that the thermal renovation rate is lower than 1 %, which is significantly lower than the goals set in the Austrian climate protection report (2 % between 2020 - 2030). To tackle this the paper presents a possibility to drive existing building from 1960's to 1980's to positive energy buildings (PEB) in Austria by implementing a multi-functional façade system by means of simulation studies. The demonstrator is chosen from a real building (a former feed silo) that is going to use as a multi storey residential building with location in Graz. The multi-functional façade includes not only a thick insulation to avoid heat losses/gains but also an innovative system where the dissipation system conditions the high thermal masses for heating and cooling purposes. The innovative system and the building are modelled and simulated in IDA ICE and assessed with defined KPI's to reach PEB status in the local area of the demonstrator, and hence to show possibilities in general to increase the renovation rate due to simple installation with less disturbances of the users. A main part in the plant system is the water-well as source connected to the heat pump system for heating or cooling (WWHP) of the building. Another renewable energy source is the building integrated PV (BiPV) that is used to produce electricity for the building and helps to reach PEB. A special attention within this paper is given to the comfort criteria of the rooms as the multi-functional façade provides "delayed" thermal energy/capacities due to high thermal masses between the emission system and the conditioned rooms. To reach PEB, different simulations are carried out where the results show that PEB status with the assumed boundary conditions can be reached with the abovementioned assumptions.

1. INTRODUCTION

As the building sector is very important to reach the EU energy savings goals, a directive was approved and named as EPBD 2010/31/EU (2010) in 2010. Another directive to boost the goals was approved in 2012 named Energy Efficiency Directive 2012/27/EU. Hence, this issue became more and more important both directives were then amended and covered within the Energy Performance of Buildings Directive 2018/844/EU (2018), which includes new further elements and motivation to modernize the building sector mainly by means of increasing the building renovation rate. Therefore, the commission presented its renovation wave strategy as part of the European

Green Deal in October 2020. In fact, according to the European Commission, the building sector holds about 40 % of the EU energy consumption and 35 % of the buildings are older than 50 years, where almost 75 % of the building stock is energy inefficient. Another statistic from the European Commission shows that the renovation rate is only about 1 % of those buildings. In Austria, the situation is similar to the abovementioned situation for the EU, that the thermal renovation rate is lower than 1 %, which is significantly lower than the goals set in the Austrian climate protection report (2 % between 2020 - 2030).

According to Fink et al. (2017), in Austria there is a high share of buildings from the 1960's to 1980's with either less insulation or no insulation. These buildings are responsible for high energy consumption in Austria and hence there is a high potential to save energy by using innovative concepts. Höfler et al. (2006) shows that in many residential buildings in this era the external walls consist of concrete wall systems, vertical coring brick or mantle block. These u-values range typically between 0.7 W/(m².K) and 1.5 W/(m².K) according to Energieagentur Steiermark (2016).

To tackle this problem simulation studies with an innovative concept based on a demonstrator for mainly residentials and with ferro-concrete as well as vertical coring brick located in Graz is carried out within this paper with the aim to reach PEB and trying to increase the renovation rate of such buildings in Austria.

2. BOUNDARY CONDITIONS AND BUILDING

2.1 CLIMATE DESCRIPTION

The location of the demonstrator is in Graz, Austria but for the simulations, the weather data from Graz-Thalerhof Airport (latitude: 47.0 N; longitude: 15.43 E at an elevation of 340 m) is used as this data is close to the object site and the weather data includes typical reference years (TRY) with measurements. The lowest ambient temperature ϑ_{min} is 12.2 °C in winter, and max. temperature ϑ_{max} is 30.9 °C in summer according to ASHRAE (2013) implemented in the simulation software IDA ICE.

The domestic hot water (DHW) load profile for a day is modeled according to SIA 2024 (2015). The load profile does not change over the year. Tab. 1 shows the summary of the DHW demand where the max. power for DHW is calculated with 26.08 kW at 7 o'clock, whereby the total energy per day is calculated with 78.24 kWh/d.

Tab. 1: Details on the DHW demand for floor 1 to 8 according to SIA2024 (2015)

Name	Supply temperature in °C	Cold water temperature in °C	Floor area in m²	DHW demand hot water in l/(per.day)	Spec. annually demand in kWh/(per.day)	Tot. annually demand[1] in kWh
MFH	50	10	920.58	35	1.63	28.514

[1] Calculated with 6 persons each floor and 8 floors and a temperature difference of 40 K ($\vartheta_{dhw,sup}$=50 °C & ϑ_{cw}=10 °C)

2.2 BUILDING

Abb. 1 to the left shows the local energy community with the demonstrator (tower with no. 10), the real building (middle) and the model with shadings in IDA ICE – simulation software (right). The room usage and heights can be found in Hengel et al. (2020).

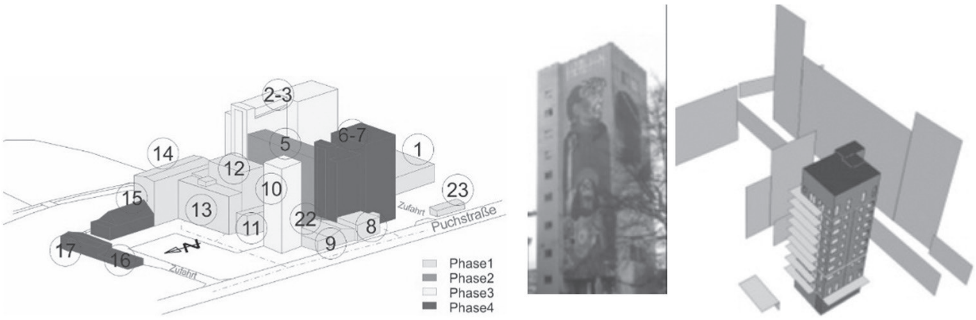

Abb. 1: Whole building complex Tagger-Area and buildings related to refurbishment phases one to four(left), photo of the real building (middle) as well as model of Turm 10 and its site shadings as well as balcony (right) (BAR 2021)

The multifunctional façade system (MFS) includes the innovative concept with an air gap in-between and a ferro-concrete (FC) wall with 21 cm, for floor 3 to 8. For floor 1, 2 and 9 the external wall consists of vertical coring bricks (VCB) with 30 cm (based on the concept B in Hengel et al. 2020). The analyzed MFS uses an active layer element that is always in between the existing external wall, e.g. FC or VCB or external plaster, and the attached insulation (cf. Abb. 2). The U-values without the active layers that are implemented in the simulation are show in Tab. 2.

Windows, ventilation system, infiltration and control strategy of the shadings as well as the temperature boundary condition of the stairway with 15 °C is taken from Hengel et al. (2020). As the office at floor 9 and café at the ground floor differs from the Hengel et al. (2020) a variable volume flow rate (VAV) based on presence of persons is assumed. The maximum flow rates are 1131 m³/h and 2178 m³/h for the office and café, respectively.

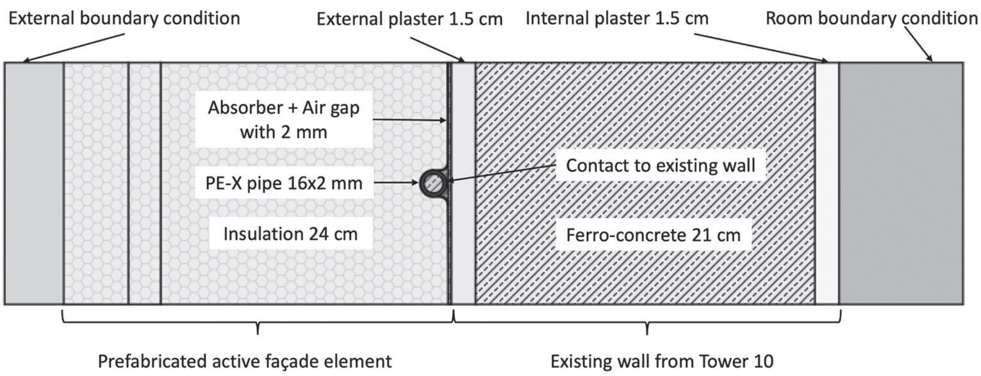

Abb. 2: Construction of the prefabricated active façade element with FC (Hengel et al. 2020)

The remaining control strategies concern the shading of windows and the day light in each room or in the office area as well as in the corridor and bath/WC.

Tab. 2: Properties of the walls with U-value, thickness and connecting rooms

No.	Name	total thickness in m	Tot. U-value[1] in *W/(m² K)*	Assign to floor
1	External wall 1 with FC	0.475	0.15	3rd to 8th
2	External wall 2 with VCB	0.56	0.14	1st, 2nd and 9th
3	External wall 3	0.235	3.40	Stairway outside
4	Internal wall 1	0.2	0.24	All internal walls except to stairway
5	Internal wall 2	0.38	0.24	Corridor/ bath to unheated stairway
6	Internal floor 1	0.3	0.62	All internal floors except among 2nd to 3rd
7	Internal floor 2	0.62	0.55	Internal floor between 2nd & 3rd
8	Roof	0.43	0.17	9th floor to Roof
9	Floor	0.51	0.51	Slab towards ground

[1] Heat transfer coefficients according to IDA ICE set with $h_i=8\ W/(m^2 \cdot K)$ and $h_o=25\ W/(m^2 \cdot K)$ – only for overview, otherwise variable in dynamic simulation

The shadings of windows are closed if the solar radiation level exceeds 100 W/m² at the outer surface of the window. The shading opens in case the solar radiation is lower than 100 W/m² and the hysteresis. For the day light control strategy in the office 500 lx has always been maintained. If the daylight drops below 500 lx the artificial light is switched on to maintain 500 lx. For the rooms, bath and WC it is similar but that only 200 lx is used as setpoint and with presence of occupants. For the corridor 100 lx is assumed.

All inner loads – lighting, appliance, el. consumptions are based on the SIA2024 (2015) but the inner loads produced by occupants are different from a normal multi-family house as the number of persons per area is higher for the demonstrator. According to SIA2024 (2015) there is an area of 30 m² for one person, but for this assumption there are 48 people on 920 m², which results in about 19 m² for one person. Due to this fact the area-specific heat gains from people is higher and calculated with about 20 kWh/(m².a) in contrast to literature which suggests about 9.5 kWh/(m².a) at an usual clothing and activity level. The assumption for the simulation features an activity level of 1.2 MET and a clothing factor of 1.0 in winter and 0.5 in summer. The room setpoints is set to 25 °C in summer and 22 °C in winter for the residential, office and café area except of corridor and bath WC with 18 °C and 24 °C respectively.

3. SYSTEM MODELLING

3.1 HEATING AND COOLING

Abb. 3 shows the system concept to reach PEB for the building tower 10. It is split in 3 categories, System 1, which concerns only the tower 10 as energy system, system 2 where the hydro power plant produces additional electricity, and system 3 where the whole area interacts with tower 10. But the goal is to already yield PEB with System 1 due to the innovative concept and not using the hydropower plant from system 2.

To provide heating or cooling energy a heat pump system with a water-well as source is modelled. The heat pump charges the DHW storage or the space heating (SH) storage that provides energy to the consumers. In summer cooling as Free-cooling, directly from the water-well is modelled and simultaneously cooling with DHW preparation is desired. To reach PEB for System 1, a building integrated PV (BiPV) on south and west directions of the building is installed. Surplus of the gained el. energy is sold to the power grid or stored to the battery (not considered here).

Abb. 4 shows the scheme of the hydronic system in detail with its design parameters. For the circulation pumps high efficiency pumps are assumed and the set points are 52 °C/48 °C for the storages DHW and SH, and 6 °C /12 °C for the cold storage. The heights of the Sensors are 10 % for DHW and SH, and 95 % for SC based on max. high of the tank (not optimized in this paper).

The linkage part between building and plant is the MFS with the active layer based on Hengel et al. (2020) (cf. Abb. 2). This active layer consists of an aluminum absorber/heat spreader with a thickness of 0.4 mm and a PEX pipe with 16x2 mm to transfer heat to or from the existing wall that conditions the room behind. According to BAR (2021) the middle pipe distances of the absorber is 12.5 cm with an overall heat transfer coefficient (HTC) of the MFS of 11.95 W/(m².K). This HTC value was determined via a parameter identification procedure comparing IDA ICE models and laboratory measurements. It shows that if the wall is not perfectly plain, the resulting HTC lies between the proposed values of the concepts HCP (A) and HCP air (B) in Hengel et al. (2020). A heat load calculation of the building with the design temperature by means of IDA ICE was carried out to design the MFS.

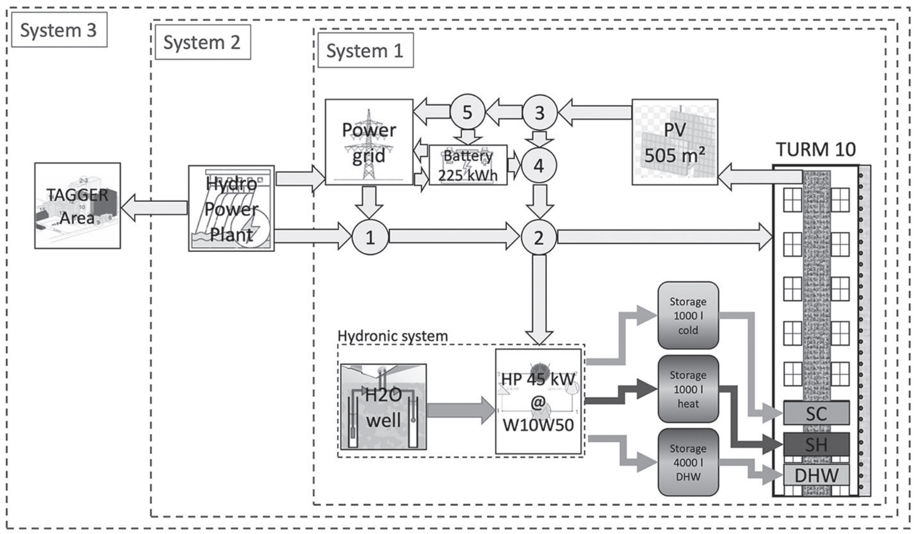

Abb. 3: Whole building complex Tagger-Area and buildings related to refurbishment phases one to four based on BAR (2021)

The results show that the worstcase room is located at the northeast corner in the 2nd floor – same room at 1st floor is quite similar – both floors feature higher share of windows than the remaining ones. Almost all rooms have design heating capacity between 400 W and 600 W or 15 W/m² to 20 W/m² based on the floor area. These results were rebased on the available wall area for each room. The max. specific design heating capacity is calculated with 30 W/m² (wall area) for all floors and 25 W/m² for the first floor to fulfil the comfort criteria. To maintain this heating capacity a supply temperature of 50 °C with a return temperature of 45 °C has been set for the heat pump system.

A similar process was done to get the design cooling capacity where the room at the 2nd floor shows the worst condition. The cooling capacity according to the design diagram shows a max. cooling power of 10 W/m² (for wall area with the construction vertical coring brick) at a mean average temperature difference of 7.5 K. This average temperature difference is the max. possible one to avoid condensation on the wall. For the construction ferro-concrete a design cooling capacity of 20 W/m² according to the design diagram is determined. As the design cooling demand cannot be reached with the active façade element it is just used with its max. cooling capacity. However, cooling of a residential building is not mandatory in Austria and therefore is not first level priority.

The distribution energy losses of the system are set to a "good" value called in IDA ICE. That means for DHW, heating and cooling a fixed value of 0.212 W/(m²) based on the floor area is used. This can be justified since the installation of the pipes and devices are new and well insulated.

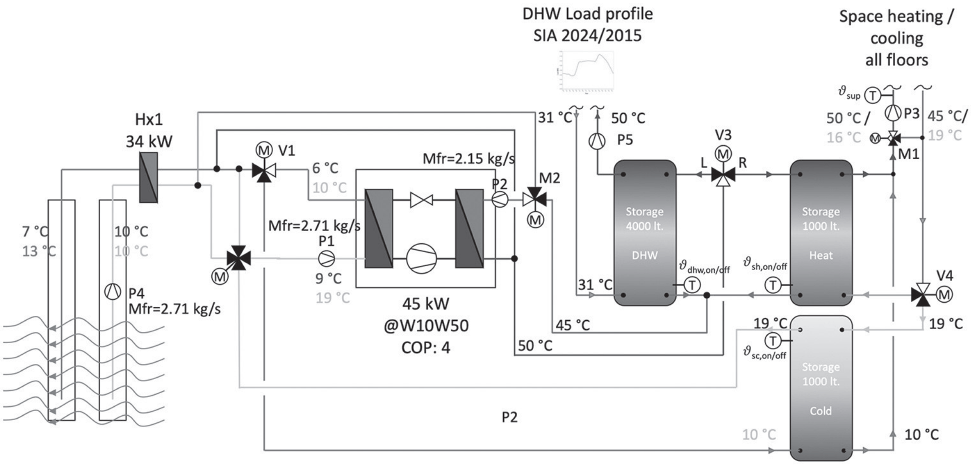

Abb. 4: Overall scheme of the hydronic system with heat pump, water-well as source, storages (DHW and SH and cold) and distribution system based on BAR (2021)

3.2 ENERGY PRODUCTION

To achieve the goal of a PEB a building integrated photovoltaic (BiPV) system is implemented in the simulation model BiPV1 and BiPV2 for west and south (cf. Tab. 3)

Tab. 3: Orientation and configuration of the BiPV

Name	Orient-ation	Number of modules	Panel Size in m²	Tot area in m²	Panel peak power in W	Panel efficiency in %	Inverter efficiency in %	Total PV system efficiency in %
BiPV1	West (251.1°)	230	1.421	326.83	240	16.9	98	16.6
BiPV2	South (161.1°)	136		193.26				

The electricity of the controller is assumed with 5 W per device and for 8760 h, and 9 controllers are applied for the overall systems with an energy demand of 394.2 kWh/a.

4. SIMULATION AND RESULTS

4.1 KPI AND CRITERIAS

The electricity consumption $W_{el,cons}$ is calculated for all devices, ventilation $W_{el,vent}$, pumps $W_{el,pu}$, controllers $W_{el,ctr}$, heat pump $W_{el,hp}$ that is used for both heating and cooling purposes, and electricity for lighting $W_{el,light}$ and appliances $W_{el,appl}$ and is defined in the equation 1.

$$W_{el,cons} = \int_{t=0}^{8760} \left(P_{el,vent} + P_{el,pu} + P_{el,hp} + P_{el,ctr} + P_{el,light} + P_{el,appl}\right) \cdot dt \qquad (1)$$

To reach PEB goals the production of electricity $W_{el,prod}$ has to be higher than the total consumption. For system 1 the produced electricity by means of BiPV $W_{el,BiPV}$ is defined in equation 2.

$$W_{el,prod} = \int_{t=0}^{8760} \left(P_{el,BiPV}\right) \cdot dt \qquad (2)$$

The total space heating energy demand of the pilot Q_{sh} is calculated as the energy provided to every zone/room also including the café and the office, the distribution and storage heat losses. The simulation for heating is done during the heating season, and for cooling not in the heating season resulting in a total cooling energy demand Q_{sc} including distribution and storage heat losses/gains. DHW energy demand Q_{dhw} is observed over the whole year also including heat losses for distribution and storage.

To meet the comfort criteria the room temperature (without corridors) must not undercut a temperature of 21 °C in the heating season and for DHW preparation the outlet temperature at the DHW storage must not undercut 45 °C to ensure a temperature level at tapping with about 38 °C. If the comfort criteria cannot be satisfied the simulation is excluded and has to be reconfigured with a proper setup.

4.2 REACHING PEB WITH VARIANT 1

With the attached prefabricated active façade element and the described hydronic system this chapter discusses the heating and cooling demand based on the definition of the KPIs. As also mentioned above the modelled net floor area is 1161.04 m² which is used to calculate the area specific values.

Tab. 4 shows the results for heating, cooling and DHW delivered energy over a year for the pilot.

Tab. 4: Results for heating, cooling and DHW energy demand over a year for the demonstrator

Q_{sh} in kWh	q_{sh} in kWh/m²	Q_{sc} in kWh	q_{sc} in kWh/m²	Q_{dhw} in kWh	q_{dhw} in kWh/m²
23 738.7	20.45	39 219	33.78	27 549	23.73

As one can see the delivered heating energy is lower compared to the delivered cooling energy which leads to the conclusion that the inner loads especially the high numbers of persons, and the solar gains have a positive effect. Herein, a proper shading strategy has to be set to avoid high cooling energy demand. The high value of 23.73 kWh/m² for the DHW consumption can be justified by the high number of people (i.e. students) in less living space as in the standard SIA2024 (2015) assumed.

To reach the PEB status the electricity is important for the assessment. So, in Tab. 5 the electric energy consumption of all devices in the demonstrator is shown. The heat pump consumes the highest share of energy with about 47 MWh as it is responsible for heating and cooling, followed by the appliances, the ventilation and pumps and the artificial light in the demonstrator. The energy consumption of the controllers is just a very small part of the energy share.

Tab. 5: Results for electric energy consumption for the demonstrator

$W_{el,vent} + W_{el,pu}$ in kWh	$W_{el,hp}$ in kWh	$W_{el,ctr}$ in kWh	$W_{el,light}$ in kWh	$W_{el,appl}$ in kWh	$W_{el,cons}$ in kWh
7 837.7	47 045	394.2	4 779.8	12 680.7	72 737.4

The energy consumption for ventilation and pumps, artificial light and appliance match very well with the standard SIA2024 (2015), where specific values of 6.64 kWh/m², 4.05 kWh/m² and 10.75 kWh/m² (cf. Tab. 6) obtained from the simulations. In total an electric energy consumption of 72 737.4 kWh or 61.66 kWh/m² is calculated for the whole demonstrator.

Tab. 6: Results for specific electric energy consumption based on total net floor area for the demonstrator

$W_{el,vent} + W_{el,pu}$ in kWh/m²	$W_{el,hp}$ in kWh/m²	$W_{el,ctr}$ in kWh/m²	$W_{el,light}$ in kWh/m²	$W_{el,appl}$ in kWh/m²	$W_{el,cons}$ in kWh/m²
6.64	39.88	0.34	4.05	10.75	61.66

In contrast, the electricity production $W_{el,prod}$ of the BiPV it is about 62 MWh or 53.35 kWh/m² which is too low for system 1 to reach PEB.

4.3 REACHING PEB WITH VARIANT 2

Therefore, optimization runs and utilization of the thermal masses are carried out in another step. The setpoint for the storages of DHW are changed to 48 °C/44 °C in the storage, the SH setpoints are set to 42 °C/38 °C and the SC setpoint to 10 °C/14 °C. Also, a heating curve was implemented to linearly decrease supply temperature from 40 °C to 30 °C at an ambient temperature from 30 °C to +20 °C, respectively. And, the control strategy for the shading devices are changed to a setpoint of 70 W/m² to avoid overheating. Optimizing the setpoints for heating and cooling is possible as the high thermal masses can maintain room temperatures within the comfort range.

Tab. 7 shows the updated results with the new control strategies. The energy provided for the space heating is similar to the results beforehand while still fulfilling the comfort criteria. On the other hand, the space cooling energy decreases due to the new control strategy for the shading devices, and the DHW consumption decreases due to lower temperature differences as well, but remains high with 22.4 kWh/m² due to the high numbers of tenants in the building.

Tab. 7: Results for heating, cooling and DHW energy demand of the optimized scenario over a year for the demonstrator

Q_{sh} in kWh	q_{sh} in kWh/m²	Q_{sc} in kWh	q_{sc} in kWh/m²	Q_{dhw} in kWh	q_{dhw} in kWh/m²
24 653	21.1	38 166	32,9	26 019	22.4

For the DHW preparation the storage temperature at the top of the store does not undercut 47 °C where the outlet to the tapping is located and hence fulfil the comfort criteria. For the room temperatures, Abb. 5 and Abb. 6 show that the min temperature in winter and max. temperature in summer where cooling takes place is in a good range with the comfort criteria. Max temperature in winter and min. temperature in summer were not observed since it can be easier handled by open the windows that was not implemented here.

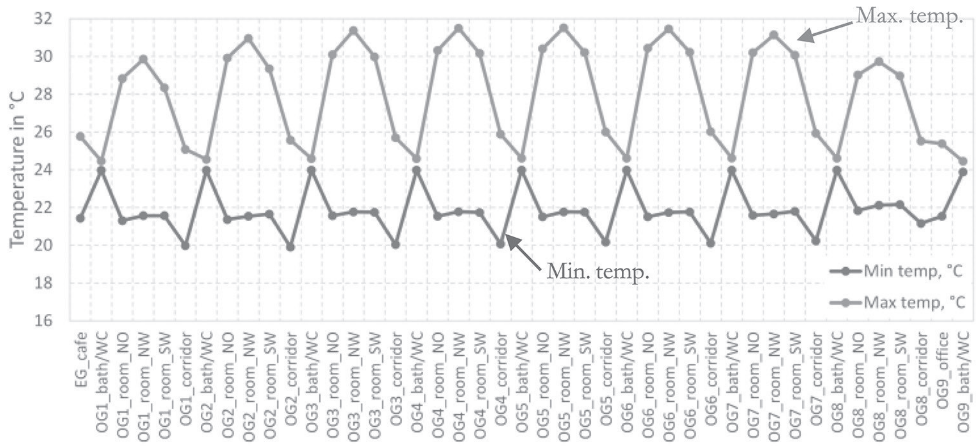

Abb. 5: Min. and max temperatures of each room in the demonstrator in the heating season of the optimized scenario (high temperatures can be neglected)

The updated electricity results, for the optimized scenario, are shown in Tab. 8 for their specific values. The energy production or gains are still the same as in the former scenario and it can be seen that with the optimized parameters and setpoints the PEB goal for the building can be reached as the electricity consumption can be reduced to 46.51 kWh/m² compared to a production of 53.35 kWh/m².

However, the impact by changing the setpoint is quite high as the heat pump can work with higher COPs and hence use less electricity. Also, less heat losses of the distribution system including the storage tanks takes place. In total the result shows minor savings for pumps and ventilation system but very high savings of the electricity coming from the plant system with the heat pump for heating and cooling.

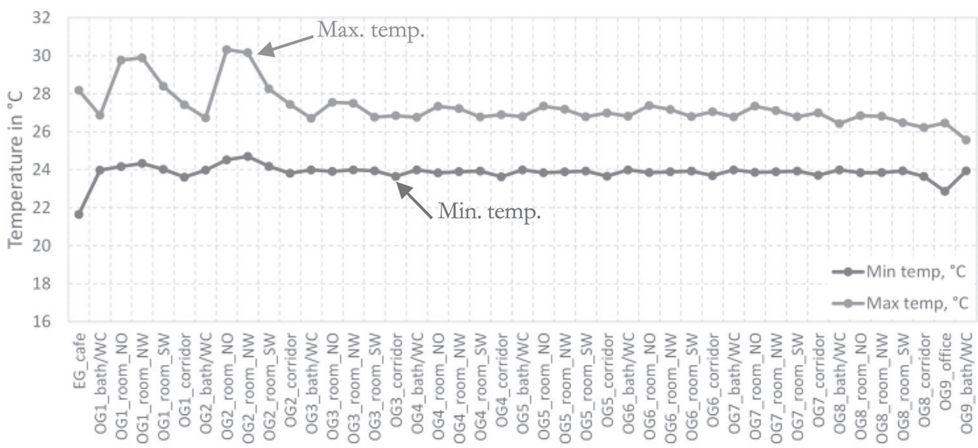

Abb. 6: Min. and max temperatures of each room in the demonstrator outside the heating season of the optimized scenario (low temperatures can be neglected)

It can be concluded that a lower temperature difference between the evaporation and condensation temperature has a huge impact to the electricity consumption of the system. The electricity demand for light and appliance remains approximately the same compared to the non-optimized case. The total electric energy consumption is calculated with around 54 MWh or 46.5 kWh/m² for the optimized scenario.

Tab. 8: Results for specific electric energy consumption based on total net floor area of the optimized scenario for the demonstrator

$W_{el,vent} + W_{el,pu}$ in kWh/m²	$W_{el,hp}$ in kWh/m²	$W_{el,ctr}$ in kWh/m²	$W_{el,light}$ in kWh/m²	$W_{el,appl}$ in kWh/m²	$W_{el,cons}$ in kWh/m²
6.23	25.33	0.34	4.21	10.41	46.51

5. SUMMARY AND CONCLUSION

Within this paper a simulation study with IDA ICE to reach PEB with an innovative multifunctional façade system is shown for a real residential building located in Graz. With some simplifications, a plant and building simulation was set up in IDA ICE and load profiles for the building were taken from literature, e.g. SIA2024 (2015). After the description of the boundaries and building model, the system and energy production is discussed (building integrated photovoltaic). The main part of the hydronic system was the water-to-water heat pump – with a water-well source – that provides heat for DHW, space heating, and for space cooling to the building. The latter ones use the innovative prefabricated active façade elements as dissipation system to transfer heat to the corresponding thermal zones. The design of the components was done with a heat load or cooling load calculation in IDA ICE. Firstly, for the simulations, an initial control strategy was set to fulfill the comfort criteria and to reach PEB.

However, the results show that the active façade elements cannot fulfill the cooling requirements since the heat transfer rate for cooling purposes – especially for vertical coring bricks – is too low. This issue has to be treated in a further study with an advanced control strategy, e.g. MPC

In contrast to this, during the heating season all comfort criteria can be fulfilled. The analysis shows that the minimum temperature does not undercut 21 °C, even for the vertical coring brick used for the external wall in the first and second floor. As mentioned, the restriction for this construction material is that the heat transfer rate is much lower compared to the ferro-concrete wall. The comfort criteria for DHW preparation is also fulfilled without difficulty.

The results are assessed with the defined KPIs and show that with the first set of temperature setpoints the goal of PEB cannot be reached due to too high electric energy consumption and too low electricity production with the BiPV. The mentioned hydropower plant is left out in this case as the electric energy production can also be provided for the whole area. However, with the optimized scenario the electric energy consumption could be reduced to reach PEB. This was found by decreasing the temperature setpoints for DHW preparation, space heating and space cooling under maintaining comfort criteria. The savings can be explained as the temperature difference between evaporation and condensation decreases and hence the COP and SPF of the heat pump increases.

However, some further research work has to be done e.g. to apply a proper control strategy for shading devices to reduce solar gains and hence reducing cooling capacity peaks and demands. Also, using a MPC strategy can be applied to utilize the potential of high thermal masses of the demonstrator for flexibility measures like demand side management.

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