PARTICIPATION POTENTIALS FOR ENERGY-ACTIVE FACADES IN FUTURE FLEXIBILITY MARKETS

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Abstract

The global pathway to net-zero emissions by 2050 in the building sector requires significantly strengthening and successfully implementing energy and climate policies. Energy efficiency, electrification and flexibility of the stock are three main drivers of decarbonization of this sector. Still, without tackling the existing buildings, the building sector will not be fully decarbonized by 2050. To achieve cost savings and minimize disruption, retrofits need to be comprehensive, one-off, and able to transform buildings into active players in the energy system. A renovation concept based on energy-active façade and elements of flexibility markets (FM) are introduced to provide demand-side flexibility in existing buildings. Moreover, the work shows that the innovative business model, such as energy flexibility as a service, could play an essential role in engaging consumers and energy-related service providers.

Keywords: Energy active Facades, Flexibility Market, Active Demand Response, Sector Coupling

1. Introduction

Electricity systems are characterized by the fact that consumption and generation of electricity must occur simultaneously, and there must always be a steady balance of power. However, both supply and demand for electricity are fluctuating, and until recently, demand fluctuations were the main focus of attention (Villar et al. 2018). This paradigm is now changing because two-thirds of all energy needs must be generated from renewables such as wind, solar, geothermal, and hydropower with fluctuating capacity until 2050. Solar PV has to be increased 20-fold and wind power 11-fold from now (IEA 2021a). The energy generated from volatile renewable sources cannot be dispatched and is subject to significant variation and uncertainties. This has increased the complexity of operating the power system and requires new sources of flexibility as existing sources are no longer sufficient. Reducing global carbon dioxide (CO_2) emissions to net-zero by 2050 is in line with efforts to limit the long-term rise in global temperatures to 1.5 Kelvin. This requires nothing less than a complete transformation of how we will produce and consume energy at an unrivalled speed and scope which brings specific challenges but also opportunities for all energy sectors.

Exceptionally large potential can be found in the building sector, which today accounts for almost one-third of total final energy consumption. Furthermore, according to current building standards, almost 75% of that building stock is inefficient, and 85 % to 95 % of the existing buildings are still in operation in 2050 (European Commission, 2021). In any case, the energy consumption of the building stock needs to be tackled, which means both an increased speed and depth of building renovation. Comprehensive renovation must become the standard approach. Without this, the sector will not be fully decarbonized by 2050. The renovation wave aims to double the renovation rate by 2030 (European Commission 2020). Calculations have shown that the renovation rate must reach 3% per year as soon as possible before 2030 and be maintained until 2050 (Sibileau et al 2021).

Numerous studies have led to the development of new industrialized construction systems for building renovation. Calelgari et al. (2015), Ruud et al. (2016), Malacarne et al. (2016), Sandberg e al. (2016), Pittau et al. (2017) present modular and prefabricated façade elements, made of wood and lightweight components intended for the retrofitting of existing buildings, to improve the energy performance of the building. While the focus of all these studies is only on improving the thermal performance of the building envelope, thereby

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mainly reducing the energy demand of the building, other studies propose to have the façades become multifunctional.

Dermentzis et al. and Ochs et al. presents an exhaust air heat pump in combination with a ventilation system with heat recovery, both integrated into a prefabricated timber frame façade. Dugue et al. (2017) and Garay et al. (2017) describe a façade-integrated ventilation concept. Furthermore, Hejtmánek et al. (2017) presented prefabricated insulating panels, and new intelligent HVAC systems for the use of renewable energy sources. Hengel et al. (2020) studied prefabricated thermally activated curtain façades that offer the possibility to upgrade insulation and the heating system in one step, reducing residents´ disturbance during the renovation process. The proposed façade uses an integrated thermal active layer for heating and cooling purposes and can be mounted directly to the existing walls from the outside. Detailed energy analysis shows that the concept of external wall heating is suitable for a wide range of applications with various wall constructions made of concrete, vertical coring brick, or solid brick in typical existing buildings from the 1960s to 1980s. These systems can meet comfort criteria and, moreover, feature a heat dissipation which can be used for flexibility measures in interplay with the thermal mass of the building's walls (Gumhalter et al., 2021).

In a follow-up study, Gumhalter and Ramschak (2022) analyzed the flexibility potential in combination with on-site PV-systems. With a weather-based storage control system the thermal storage capabilities were used to exploit the optimization potential for self-consumption. For this purpose, an Active Demand Response Signal (ADR signal) was introduced, which provides the heat pump and the room temperature control with a charging signal based on the generation of the PV system. This control strategy, in conjunction with the building-integrated PV generator presented, leads to a weather-dependent, daily signal of 6 to 12 hours depending on the season. The study showed that this control strategy can drastically increase the renewable load cover factors for space heating from 25 % up to 77 % renewable energy share for space heating.

In this paper, the approach of active flexibility usage will be further investigated and an additional application field will be presented. This work focuses mainly on the evaluation of the provision of flexibility as a service for flexibility markets (FM). The common concept is to forecast potential constraint violations and the location of the respective congestion points and to determine locationally differentiated grid prices. If the flexibility of the building reacts to these price signals in a FM by changing its load profile, constraint violations can be indirectly avoided. In this case, the change in the load profile is not inevitably accompanied by a change in the behavior of the users. For example, if the building is confronted with a significant increase in the grid price, it will reduce its load and consequently purchase less energy from the grid. In contrast, if the building faces a decrease in the grid price it tries to increase its load by using the active façade to charge the storage capacity of the existing walls while maintaining the thermal comfort. Although the main intention is the provision of flexibility to a Distribution System Operators (DSO) or Transmission System Operator (TSO) in a FM through a uniform price signal, a numerical example provided in this paper illustrates the expected financial impact for the engaged end-user.

The paper is structured as follows. First, based on an energy flexibility quantification framework, the energy flexibility profile of a typical multifamily building studied in Gumhalter and Ramschak (2022) is quantified; secondly, according to the energy flexibility and a yearly day-ahead price curve of the electricity, a simple to implement control strategie is designed, aiming to minimize the end-user's electricity costs. Finally, the expected financial implications are illustrated in a series of numerical examples showing the impact of activating demand side flexibility.

2. Parameters for defining the flexibility of a building

To evaluate the flexibility potential of the active façade system, the sample building and a series of Key Performance Indicators (KPIs) is introduced in this chapter.

2.1. Sample Building

The building used for the experiments is based on a multi-family house in urban areas in Austria which is typical for the construction period between 1960 and 1980 and has already been described in detail in Gumhalter and Ramschak (2022). The experiments were carried out for a single thermal zone representing a 70 m² flat. While in Gumhalter and Ramschak (2022) the four most common building material types for these unrenovated houses were analyzed, the focus in this study is on the building with reinforced concrete as existing walls with the specific properties summarized in Table 1. The entire building hull is considered to meet the numbers listed in Table 2 which leads to a maximum heating load in the observed dwelling of 1,255 W total, or 17.9 W/m² specific, which is based on the static method described in ÖNORM12831 (2018), a minimum annual ambient temperature of -12,2 °C (ÖNORM8110 2019) and a thermal zone temperature of 22 °C.

Table 1: Material-specific properties for the wall

Wall material	Thickness [m]	Thermal conductivity [W/mK]	Spec. heat capacity [J/kgK]	Density [kg/m³]
Ferro concrete	0.21	2.30	1000	2300

Table 2: Thermal heat transfer values of surfaces and corresponding areas

Envelope part	U-value [W/m²K]	Area in total building [m²]	Area in observed dwelling [m²]
Outside walls	0.15	392.7	49.3
Basement ceiling	0.17	227.4	0
Top floor ceiling	0.11	236.1	0
Windows (panes)	0.6	107.2	9.9
Windows (frame)	2.0	30% of window panes	30% of window panes

2.2. Characteristic load profiles

The characteristics of the heating process are important parameters for the utilization of flexibility. It can be described by two parameters. Q_h defined in eq. 1 represents the daily heat capacity transferred to the building via the active façade to maintain thermal comfort. The loading time t represents the duration required for this purpose.

$$Q_h = \int_0^t P_h dt \qquad \text{(eq. 1)}$$

Figure 1 shows heating (left) and cooling curves (right) and the aggregated curves (bold) for the observed dwelling, simulated with the building simulation software IDA ICE featuring a validated model of the active façade setup (EQUA, 2021). The heating and cooling power provided by the active façade system to the thermal zone shows a peak power of approximately 2200 W (≈45 W/m²) for heating and 1500 W (≈25 W/m²) for cooling due to transient behavior caused by the thermal mass (high temperature gradient between the heating/cooling medium and the wall material). The charging of the walls is mainly concentrated in time periods of four hours for the heating and ten hours for the cooling season. This time span should be taken into account when choosing the ADR signal in order to carry out the majority of the loading process within the times with the lowest energy prices.

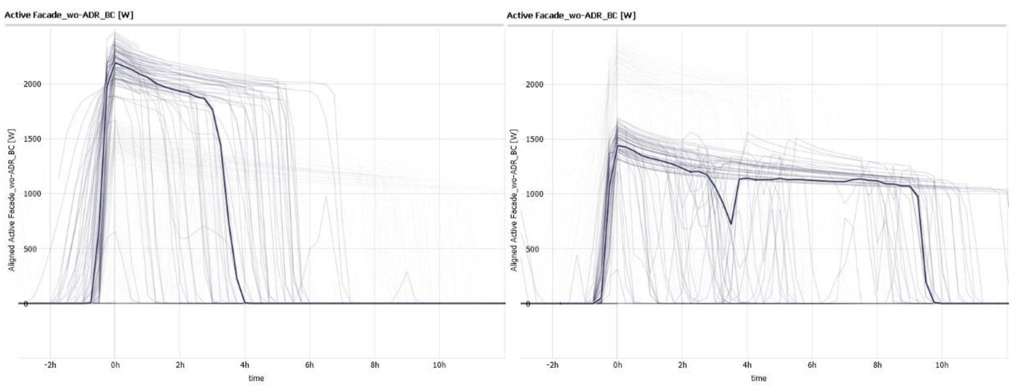

Figure 1: Aggregated heating (left) and cooling (right) curves showing the mean value for the observed dwelling.

2.3 Day-ahead price-based ADR-Signal

Modern building energy management systems, using smart technologies, connectable devices, sensors and smart meters, enable individual households to interact with the electricity grid and the energy market and optimize the operation. Business-model innovations, such as flexibility as a service, could play an important role in engaging consumers and energy-related service providers. For the Building operator, as well as for the end users, smart charging of the building's storage capacity is attractive mainly because it offers economic benefits by allowing controlled charging at times with low prices. This paper assumes that the building energy management system participating in smart charging reacts to prices by a central wholesale market; however, this scenario could also be applied for example to local energy communities with their own electricity market or an independent flexibility market where incentives would come directly from the TSO or DSO to support congestion management in the transmission or distribution grid.

The price information is retrieved exemplary for Austria. The overall day-ahead price on quarter hour values from August 2021 to July 2022 (APG, 2022) is plotted in Figure 2, showing a drastically increased day-ahead price. The statistical distribution in Figure 3 also shows the fact that prices vary significantly on a daily basis from, in average up to 83 €/MWh in August 2021 and 360 €/MWh in July 2022. The analysis of revenues for this business scenario, shown in chapter 3, should be considered as an illustrative exercise rather than a prediction of price trends over time.

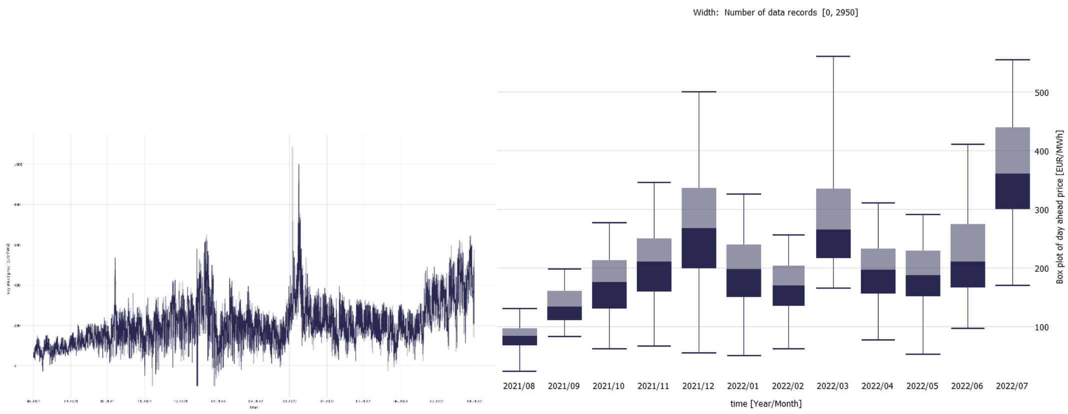

Figure 2: Day-ahead price in €/MWh from 08/2021 – 07/2022 (left), monthly bandwidth of the day-ahead price (max 97.5%, quantile 75%, mean, quantile 25%, min 2.5%) (right)

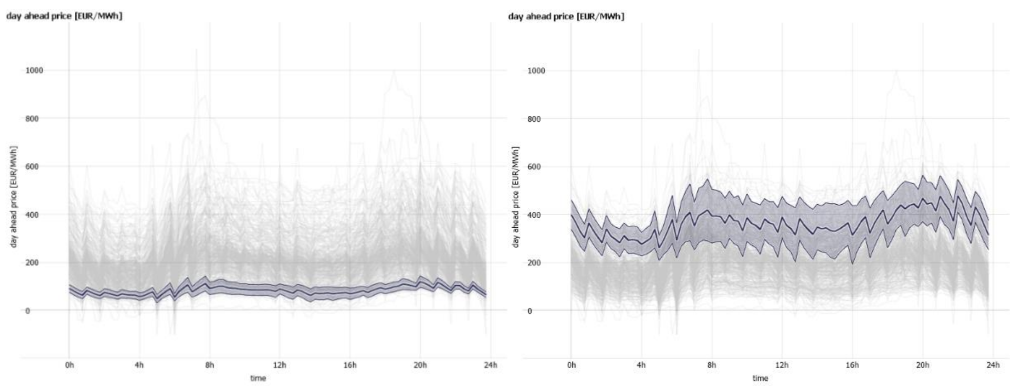

Figure 3:Daily day-ahead price curves for August 2021 (left) and July 2022 (right), the central curves show the aggregated mean curves with the boundaries with a standard deviation of 1.

In order to adapt to price signals on a flexibility market, a simplified mechanism was applied. Scenarios were defined that vary in the way the ADR signal is modified. As already described, the aim is to keep the electricity costs for heating and cooling as low as possible. Instead of using an elaborate model predictive control, a simplified price based ADR control signal is identified. A charging proposal can be imposed on the smart controlled heating system depending on this ADR signal. To impose such ADR-signals (eq. 2) the quantile value of the mean day-ahead price for the next 24 hours is the basis. The ADR signal ($status_{ADR}$) is triggered if the actual price at actual time is below the 24-hour price quantile.

$$p_t < p_{qi} \rightarrow status_{ADR} = 1 \qquad \text{(eq. 2)}$$

The following four scenarios were defined: The ADR signal is active when the current price is below the value of the 24 h mean 50% quartile, 33% quartile, 25% quartile and 10% quartile based on the day-ahead price. If the ADR-signal is active a signal is passed to the zone controller which raises the room temperature set point by 1 K. This control strategy leads to an active loading of the thermal mass of the building envelope without having to intervene in the higher-level heating controls. Figure 4 shows the time periods and the corresponding day-ahead prices if active loading is forced. Conversely, this does not mean that heating or cooling is prohibited any other time if the comfort conditions are not met.

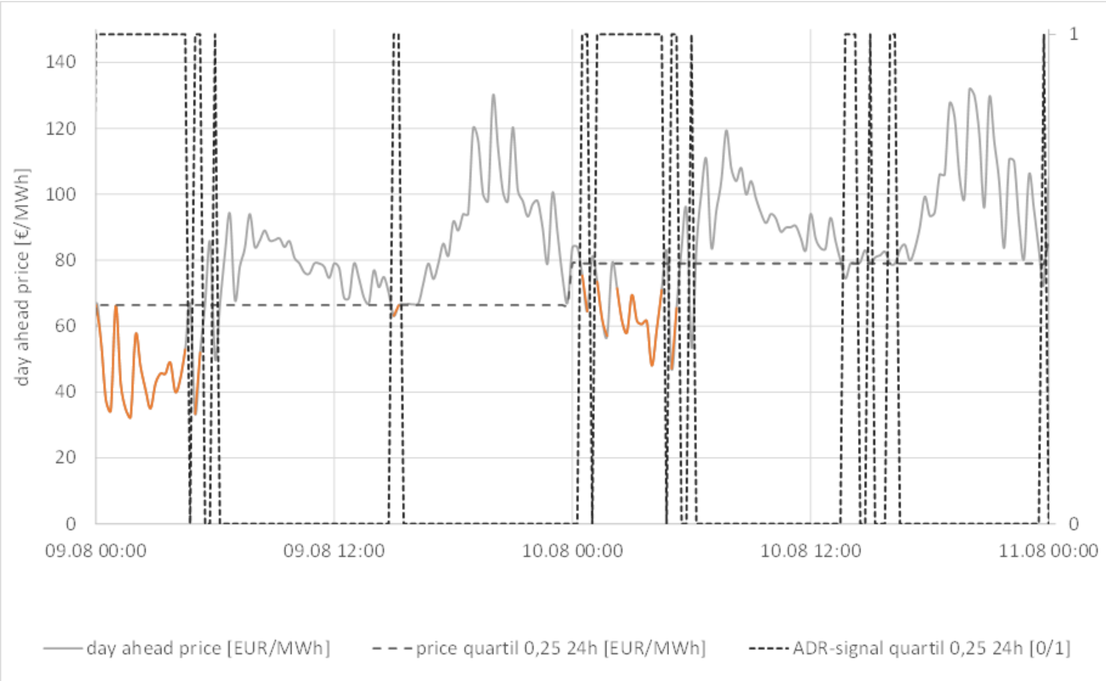

Figure 4: ADR-signal based on the day-ahead 25th empirical quartile

The On/Off ratio of the ADR-signal depends on the threshold values that are permitted, as also shown in Figure 4. While a positive ADR-signal occurs for an average of 12.3 hours per day for the 50 % quantile (q50), this duration is reduced to 8.3 hours for q33, to 6.3 hours for q25 and to 2.4 hours for q10. Comparing the load profile from chapter 2.2 with the average available On-periods of the ADR signal, it can be concluded that with a q50 signal, heating takes place at times with unnecessarily high prices. Similarly, controlling the heating with a q10 ADR signal would not be sufficient to heat only at times with the cheapest prices. Figure 5 shows the daily distribution of the ADR-signals for August 2021.While ADR-signals are distributed throughout the whole day at a quantile of 50 % (q50), the focus of the daily ADR-signals shifts slightly to night hours for smaller quantile ADR-signals. This shift to the night time is particularly pronounced in the winter months.

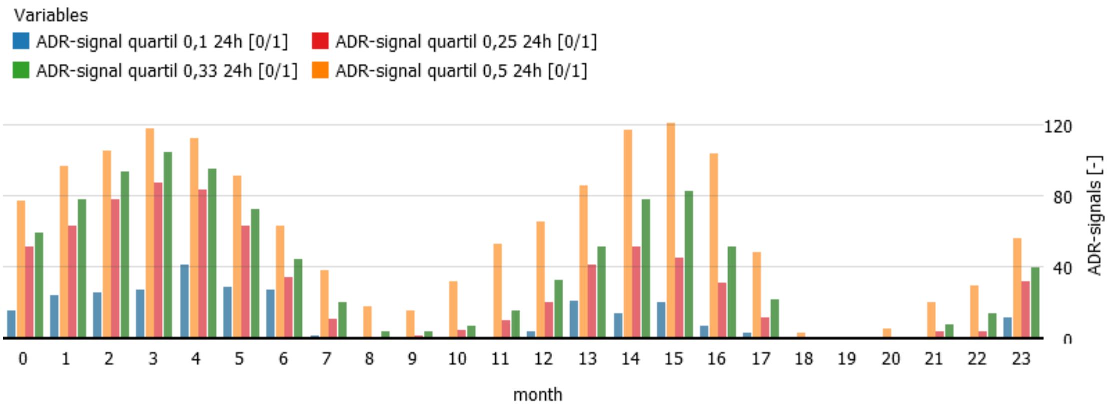

Figure 5 Distribution of ADR-signals over 24 hours

The simulation model provides the results (visualized in Figure 6) as electricity consumption profiles for every 15-min interval. In all scenarios a heat pump system with a constant COP of 3 for heating and cooling is considered. In the plot, the exemplary ADR-signal based on a 25 % quantile is represented by the light blue line, the façade´s energy consumption with standard control (without ADR-signal) by the red line, the façade´s energy consumption with ADR-signal by the green line and the electricity tariffs for the heat pump producing cold in this case as blue line. When comparing the electricity consumption, it becomes apparent how the facades shift their consumption into low price zones in response to the price (ADR) signal. To quantify the cost savings potential, we compare the resulting costs for different scenarios which are described in detail in chapter 3.

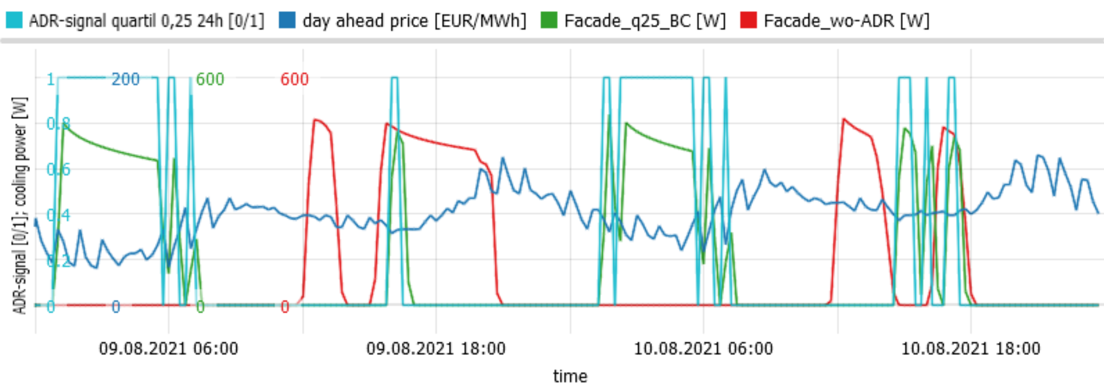

Figure 6: Shifting of cooling loads exemplary for the q25 ADR-signal

2.4 Structure storage capacity

To answer the question targeting the size of the flexibility potential, which could be offered as a service to a flexibility market, the evaluation of the flexibility related indicators is done for the observed dwelling. The structure storage capacity C_{ADR} (eq. 3) represents the amount of additionally stored energy during a positive ADR-signal compared to the reference scenario (with radiator heating system) over the duration t_{ADR}. With $\dot{Q}_{ADR}$ representing the energy flow provided by the energy active façade and $\dot{Q}_{Ref}$ representing the energy flow provided by a reference system. In the presented case the reference heating system is based on radiators for heating which are typically installed in existing buildings in the relevant construction period and a fan coil as fast-reacting cooling system.

$$C_{ADR} = \int_0^{t_{ADR}} (\dot{Q}_{ADR} - \dot{Q}_{ref})dt \qquad \text{(eq. 3)}$$

In Figure 7 the dynamic behavior of the fan coil system without ADR-signal (light blue line) is compared with an active-façade-based system (orange line) influenced by the ADR-signal (red line) described in section 2.3. The cooling of the active-façade-based system mainly concentrates during the ADR On-periods. In contrast, the fan coil-based system shows a relatively constant behavior with peaks during the noon but without cooling interruptions in the night times. Calculating the daily utilized structure storage capacity according to eq. 3 for the active-façade-based system during the exemplary observation period (August 2021) results in the numbers displayed in Table 3.

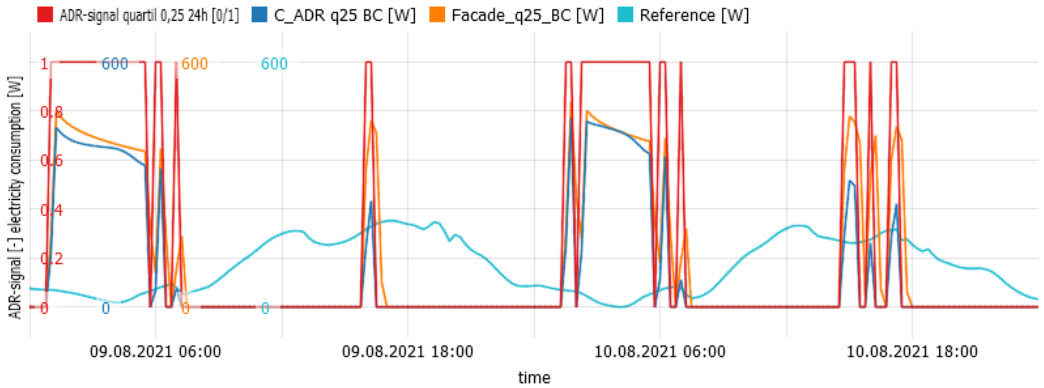

Figure 7: Comparison of space heating demand exemplary for the q25 ADR-signal

Table 3: Comparison of utilized structure storage capacity for cooling in August 2021

Szenario	MAX C_ADR $[Wh_{el}]$	MAX C_ADR $[Wh_{th}]$	Daily mean C_ADR $[Wh_{el}]$	Daily mean C_ADR $[Wh_{th}]$	spec. MAX C_ADR $[Wh_{th}/m^2]$	spec. Daily mean C_ADR $[Wh_{th}/m^2]$
Active façade q10	839	2516	593	1779	51	36
Active façade q25	2502	7507	1529	4588	152	93
Active façade q33	3061	9186	1667	5510	186	102
Active façade q50	3462	10387	2241	6722	210	136

Evaluating the same indicator for the heating in December 2021 reveals a maximum daily amount of stored energy of 5,6 kWh_{el} (16,9 kWh_{th}; 0,34 $kWh_{th,}$/m²wall) for the q50 scenarios. The remaining scenarios results are summarized in Table 4.

Table 4: Comparison of utilized structure storage capacity for heating in December 2021

Szenario	MAX C_ADR $[Wh_{el}]$	MAX C_ADR $[Wh_{th}]$	Daily mean C_ADR $[Wh_{el}]$	Daily mean C_ADR $[Wh_{th}]$	spec. MAX C_ADR $[Wh_{th}/m^2]$	spec. Daily mean C_ADR $[Wh_{th}/m^2]$
Active façade q10	1180	3540	832	2498	72	51
Active façade q25	2840	8520	1879	5638	173	114
Active façade q33	3663	10989	1912	5737	223	116
Active façade q50	5635	16904	2755	8267	343	168

To assess the business case from a technical perspective the aspect of flexibility response time to the trigger, or signal and the availability throughout the day and year can be analyzed. In general, the active façade is independent from the energy generation technology.
In the presented use case, a heat pump system is used, which is highly suitable for providing flexibility as it can be instantaneously switched on and off and can also be power modulated. The availability of flexibility is mainly constrained by the building´s energy demand.

Generally, the large storage capacity and the low heat losses of well-insulated buildings can provide flexibility for several hours throughout the day. Only the room temperature, which can rise during the day without an external energy supply due to passive solar gains, limits the flexibility in times of high irradiation, as the comfort limits may be reached. Power flexibility is higher in winter because of higher energy demand and higher temperature gradient between the heating medium and the external wall. However, the flexibility is also significant for cooling in summer.

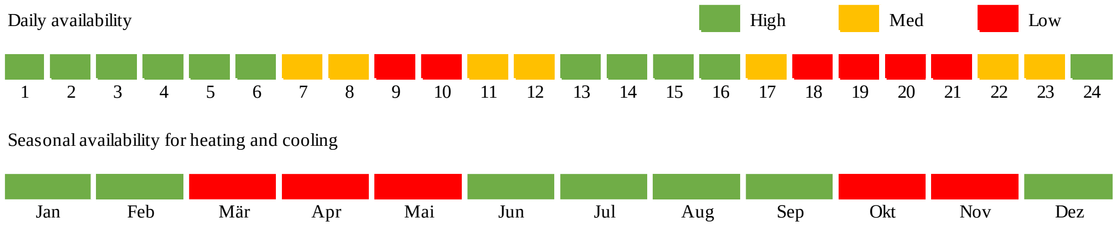

Figure 8: Availability of flexibility from active facades for heating and cooling throughout the day and year

3. Economic assessment

In order to illustrate the monetary benefits that could be gained by consumers in the building with energy active facades, the day-ahead price model has been applied in a set of experiments.

The prices for end customers are made up of different price components. A rough distinction can be made between energy costs, grid costs and taxes and fees. However, network tariffs and taxes are not considered in this study.

The economic scenario 0 represents the Reference (Ref) case with the radiator system and the fan coils, no flexibility deployed. Scenario 1 represents a system based on active facades but without ADR-signal. In scenarios 2 to 5 load shifting with the active façade based on ADR-signals is considered. Table 5 gives an overview of the scenarios. The resulting costs in each of these scenarios are summarized in Table 6 and Table 7 below. First the total electricity consumption for heating and cooling in the observed scenario are compared. Then the electricity cost in € and the savings in % are compared to the Reference case.

Table 5: Scenario overview

<table>
<tr><th>Scenario</th><th>Day-ahead price tariffs</th><th>Load shifting</th></tr>
<tr><td>0 Ref wo-ADR</td><td rowspan="6">Yes</td><td rowspan="2">No</td></tr>
<tr><td>1 Active façade wo-ADR</td></tr>
<tr><td>2 Active façade q10</td><td rowspan="4">Yes</td></tr>
<tr><td>3 Active façade q25</td></tr>
<tr><td>4 Active façade q33</td></tr>
<tr><td>5 Active façade q50</td></tr>
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Table 6: Scenario results

Scenario	electricity consumption ADR_match [kWh]	electricity consumption ADR_mismatch [kWh]	ADR_match [%]	ADR_mismatch [%]	total electricity consumption [kWh]
0 Ref wo-ADR	-	486.31	0%	100%	486.31
1 Active façade wo-ADR	-	522.80	0%	100%	522.80
2 Active façade q10	168.26	342.16	31%	69%	510.43
3 Active façade q25	336.26	181.61	58%	42%	517.87
4 Active façade q33	376.08	144.40	65%	35%	520.47
5 Active façade q50	423.65	99.15	75%	25%	522.79

Table 7: Scenario results (2)

Scenario	electricity cost ADR_match [€]	electricity cost ADR_mismatch [€]	specific costs ADR_match [€/kWh]	specific costs ADR_mismatch [€/kWh]	total electricity costs [€]	Cost savings [%]
0 Ref wo ADR	-	105.0	-	0.22	105.0	-
1 Active façade wo-ADR	-	104.8	-	0.20	104.8	0.2
2 Active façade q10	20.6	73.1	0.12	0.21	93.8	10.7
3 Active façade q25	52.6	41.1	0.16	0.23	93.7	10.7
4 Active façade q33	62.6	33.7	0.17	0.23	96.3	8.3
5 Active façade q50	76.7	24.1	0.18	0.24	100.9	3.9

If a participation in a flexibility marked is assumed the active façade system is able to shift up to three quarters of the buildings heating and cooling demand in time for a q50 ADR-signal. This is reduced to approximately 31% for a q10 ADR-signal.

In the Reference Scenario the total costs sum up to 105.0 € per year. The active façade in the scenarios 1 to 5 reduce the overall cost. However. the profitability of smart charging depends heavily on the spreads of the actively used intraday prices. An ADR-signal making use of the lower 50 % price quantile leads to a very small cost reduction in comparison to the reference system, as the reference system also uses the full range of the lower costs and has a slightly lower total energy demand. But especially in the case of applying a stricter ADR-signal the costs for the end-user are reduced by 8.3 % in q33 Scenario and even by 10.7% in the q25 and q10 scenario.

4. Conclusion

In this paper, a renovation concept based on energy active facades has been proposed to enable the widespread adoption of FM.

The results of the load profile analysis showed, that in comparison to conventional heating system the characteristic is changed dramatically in heating power and daily heating duration due to the dynamic nature of the thermal capacity. Furthermore, the mean amount of thermal mass storage capacity that is utilized in day-to-day use, when applying active façade systems, is up to 0.168 kWh/m²wall, stored within active demand response signal period, which lead to an overall storage capacity of 22 kWh_{el} or 66 kWh_{th} on daily average for the entire building.

The proposed market model based on ADR signals was primarily considered to provide flexibility for the DSO in a FM. The approach is that flexibility is activated by spatial-temporally varying prices with associated ADR signals. A simple mechanism, the setpoint temperature increase, is used, which does not require any intervention from the higher-level energy management system.

A day ahead price was considered for the identification of the ADR signals by gradually using the lower limit values of the price signal for the activation. This is equivalent to prioritisation by the DOS, for example, in order to avoid bottlenecks. However, the general concept is also transferable to a smaller market, such as a renewable energy community that sets its community prices based on locally renewable energy.

Although the focus is on flexibility provision for the DOS, the numerical examples provided in this paper serve to illustrate the expected financial impact on the end user. Concludingly, the main benefit for end-users are cost savings of up to ten percent just from responding to volatile energy price signals. This is especially relevant regarding the latest developments on the energy markets which show even more range of fluctuation in daily business compared to the previous years.

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