Experiment-based testing routine to characterize building energy flexibility for potential aggregators

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Abstract. The ultimate goal is to introduce a standardized routine to characterize flexibility of a given building for the purpose of potential flexibility aggregators. The routine should provide the characteristic demand response of the building under various smart-grid control signals (e.g. time-of-use (stage) pricing, real-time pricing etc.). The scope of this paper is limited to the experimental part, that demonstrates measured demand response provoked by testing sequences. The testing sequences were applied via cloud-based service to the building management system (BMS) of a mid-size office building in Prague. The evaluation is not limited only to power metering but also includes indoor environment quality (in terms of room air temperatures and CO_2 concentrations), HVAC system and local meteorological data monitoring. The air handling unit (AHU) and cooling system response were investigated using 'step' and 'modular' testing sequences. The real-life experiments revealed authentic demand response allowing to characterize building flexibility in full details. The key findings are, that the operation of the HVAC system components can be blocked for relatively long period of time (2 to 5 hours in studied case) without any critical consequences to the indoor environment quality. Approximately 30 % of the total power load per the testing event can be considered as flexible. The quality of the power profile was found highly irregular. Due to the power profile fluctuation the ramping/modulation at the single building level was found ineffective. In contrary to the modular control, the multi-stage control led to more detectable power reduction. The stage type of control provoked more observable, reliable, and easier-to-predict demand response.

Keywords: Building energy flexibility, flexibility characterization, aggregation support, experimental testing, HVAC system
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1 Introduction

Energy sector in the European union has been undergoing transformation towards carbon neutrality, which is the key objective for 2050 stated by European Green Deal [1]. Increasing penetration of the intermittent renewable energy sources into the transmission and distribution electrical systems requires higher storage capability and/or flexibility at the demand-side. Building sector (both residential and commercial buildings) represents major electricity consumption in the Europe counting around 54 % of the total delivered electricity into the grid[2]. Attempting the closer integration of these sectors via smart-grid technologies seems like a logical step, that may accelerate the ongoing transformation.

Building energy flexibility was generally defined by IEA as "the ability to manage demand and generation according to local climate conditions, user needs and energy networks requirements". More detailed characteristics at building level, possible stakeholders and flexibility indicators have been collected in the framework of the IEA EBC project Annex 67 which is followed up by the Annex 82 [3]. The further research area investigated by the ongoing Annex 82 are: scaling from single buildings to clusters of buildings (aggregation); energy flexibility and resilience in multi-carrier energy systems (electricity, district heating/cooling and gas); acceptance/engagement of the stakeholders; and new business models. From the perspective of transmission and distribution system operators (TSOs and DSOs), two types of demand-side flexibility are recognized as explicit and implicit [4].

Explicit flexibility is committed, dispatchable flexibility supporting balancing services, such as frequency restoration reserves, traded on whole-sales, balancing, or system support and reserves markets. These balancing services have been already well specified in the codes of TSOs or DSOs, that require very high service reliability (e.g. sub-minute monitoring, 5 to 15 minutes ramping, high power quality etc.). The balancing services must be fast, accurate and activated on demand (randomly), which can hardly be provided by buildings. Explicit flexibility is commonly provided by vendors with industrial size of energy plants, that has sufficient volume and power capacity (e.g. minimum quantity 1MW) to enter the market, though they still may use flexibility aggregator to maximize their profit.

Implicit flexibility is the consumer's reaction to retail price or other grid signals. The end-user (e.g. building owner/operator) has the possibility to choose retail tariffs corresponding to supplier needs, variability on the market, and ultimately the network balance as common goal for all stakeholders. The role of so-called 'business' flexibility aggregator is crucial here to compile the sufficient size of the building's portfolio in order to reach minimum volume of the bids allowing to enter the wholes-sale or spot (day-ahead) energy markets. Since the spot-market trading is usually based on hourly (rarely 15 minutes) interval and the bids are specified in volume blocks, the requirements for demand response reliability and quality are significantly lower, than in previous type. The building flexibility may be effectively accommodated as implicit flexibility services; however, such services have not been yet fully developed [5].

Scaling from a single building to building clusters is a key aspect for the building flexibility as a viable service. As stated in [6], the building demand response still needs to be defined as a product for further flexibility aggregation, that will be recognized by the aggregators, market operators, TSOs or DSOs. The main barriers, that were also identified in the report are: lack of requirements for smart customer assets, low observability in low-voltage grids (complicating the settlement) and inadequate load and generation forecasting at distribution level.

The building energy flexibility characterization needs to be expanded to support the reliable prediction (with sub-hourly resolution) of total building demand under various type of the smart grid (SG) 'activation' signals. The current research proposes an approach combining series of experiment- and simulation-based tests improving the building flexibility characterization in terms of flexible capacity and power profile quality for potential aggregators. The ultimate goal is to introduce a standardized routine to characterize the building flexibility of a given building. The routine should report flexibility characteristic and support creating or refining a model of aggregated building portfolio. The scope of this paper is limited to the experiment-based part demonstrating measured demand response. This response is provoked by the testing sequences applied via newly developed cloud-based service to the building management system (BMS) of the demonstration office building in Prague.

2 Testing routine to characterize building energy flexibility

Focusing on the single building level, where the testing sequences are realized, major part of the energy in buildings (around 60 %) is consumed by HVAC systems [7]. Moreover, according to the EU roadmap, HVAC systems supposed to be massively electrified in the near future (i.e. support of heat pumps, electric boilers, etc.) [8]. For that reason, the presented method specifically aims at these systems. The SG solution is built on premise, that any modern devices or BMS will be able to receive commands from the SG (i.e. based on aggregator needs). Based on these commands the building demand will be shifted or shed accordingly, while partially blocking system functionality and utilizing available electrical or thermal storage capacity (i.e. batteries, storage tanks, piping thermal capacity, envelope capacity etc.). Since each building system is usually unique, the demand response is very case-dependent. The testing routine is proposed to characterize flexibility capacity, quality of output power response as well as impact to the indoor environment quality (IEQ) of a given building prior adding it into the possible aggregator's portfolio. The testing routine schematically depicted in Fig. 1 links three stakeholders: aggregator, building operator and occupants.

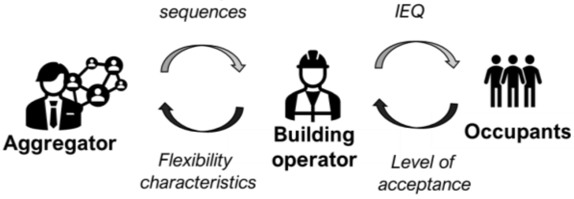

Fig. 1 Stakeholders involved in testing routine

Hereunder the testing routine is further explained in following steps.

2.1 HVAC system and BMS audit

In this step, a given HVAC system and/or BMS is inspected based on available documentation. Nominal loads of individual devices and expected part load (based on data from regular operation) are reported. The audits should also include critical levels related with allowable range of indoor environment variation. In this research IEQ is represented by thermal comfort limits and Indoor air quality (IAQ) in terms of indoor CO2 concentration

2.2 Monitoring and actuation report available for flexibility activation

In this step, the capability of BMS system is investigated to ensure the aggregator, that all required sensors and actuators supporting flexibility services are available. If missing sensors or actuators are found, the BMS system is extended.

2.3 Verification of aggregator's support service connectivity

In this step, the connectivity with aggregator's service providing the grid signal (e.g. current tariffs, price prediction etc.) is verified. During the verification activity, the actuators do not listen to smart-grid commands/settings. Only the capability to receive the signal by the BMS is checked.

2.4 Experiment-based testing sequences for building flexibility characterization

Once the (supervisory) aggregator's service communicates correctly with the BMS (or individual devices), the service is used for execution of testing routine, that provoke the flexibility event. During this testing activity, the actuators follow the testing commands. The quantity of shifted or shed load and overall quality of the power profile are analyzed for the given test. The testing sequences are designed to test the response under a) step change, b) modular change of the testing signal. The testing sequences aim to reveal the authentic characteristic behavior of the building demand response for a current boundary condition (weather condition, occupancy etc.). The experiment-based assessment may serve underlying data for modelling and calibration purpose, if necessary.

2.5 Simulation-based assessment of for building flexibility characterization

As the final step, the testing sequences are repetitively tested on the numerical model developed either in building energy simulation tools or data-driven models to observe the demand response capability for typical conditions during the entire year to address weather-dependency or different occupation. Simulation also enables to generate a baseline profile and quantify typical flexibility indicators. To recall, the simulation-based assessment is out of scope of this paper.

3 Case-study description

3.1 Building and its HVAC description

A case-study building is a commercial administrative building located in Prague (see Fig. 2). A building envelope is made of iron-concrete with additional extruded polystyrene insulation. The building itself consists of three interconnected smaller blocks with a total usable area of 3568 m^2. The building HVAC system, a scheme of which is in Fig. 2, consists of the following devices. Cooling is delivered by the roof-top chiller with nominal electric power of 65 kW. There are also two cold storage tanks with the total volume of two cubic meters.

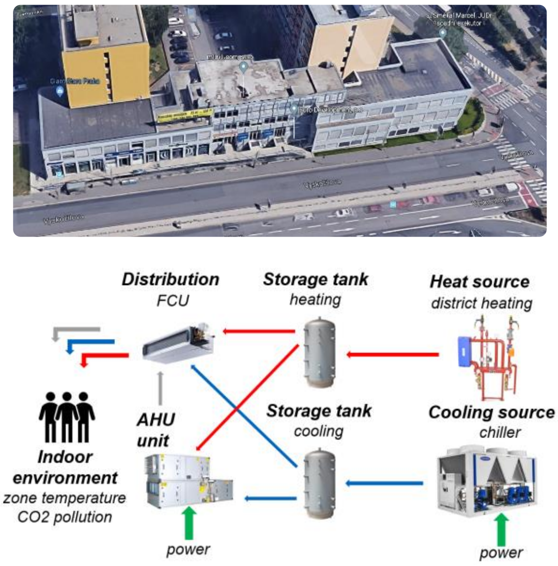

Fig. 2 Scheme of demo office building and HVAC system

Heating of the building is primarily provided by the district heating. The heat supply with the nominal heating capacity of 303 kW is then controlled using the weather-dependent control curve. The chiller is capable to operate in the heat-pump mode as back up source, however it is not practically used in this regime. As in the case of cooling, the heating system also comprises two cubic storage tanks.

Local zone temperatures and IAQ are controlled locally by FCUs with ventilation, cooling and heating capability. The fresh air is supplied by two AHUs equipped with heat recovery. The two AHUs have nominal air flow 5100 m^3/h and 8000 m^3/h. The nominal electric power of ventilation fans in both units is 6.7 kW.

3.2 Flexible control and its architecture

Control and monitoring are realized on the building level via multiple PLCs governed by BMS. The data collection is executed with a 10-minute period by the BMS interface called 'Thingsboard'. This system is also equipped with a secured API which allows to communicate with remote control systems. This feature is crucial and was utilized by the newly developed supervisory control which runs at university cloud service representing the aggregator's support service. This service translates the SG signals to commands, that can be accepted by the local BMS. The cloud service scheme as well as the local building control is depicted in Fig. 3. Regarding the cloud service there are several data sources which are needed: a) current status or prediction of the *SG* signal (e.g. time-of-use or real-time pricing tariff) from aggregators or other providers. b) source of the weather forecast. c) the actual state of the building, especially current conditions of the IAQ.

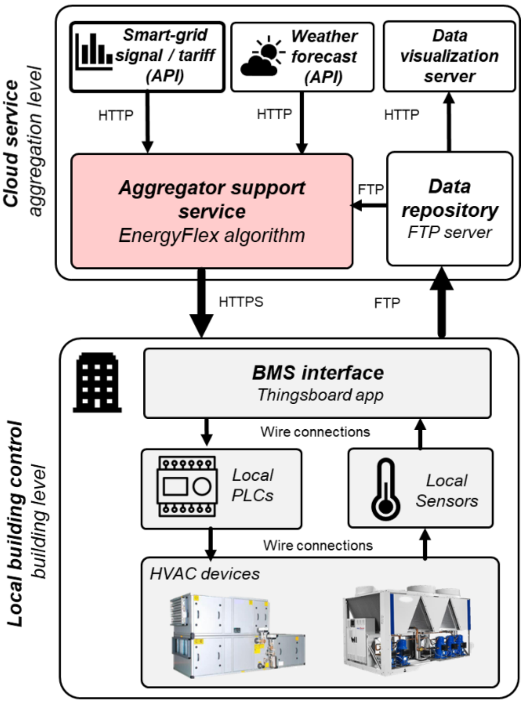

Fig. 3 Control architecture supporting building flexibility aggregation

The flexible control algorithm (called '*EnergyFlex*') communicates through HTTPS requests with the 'Thingsboard' interface on regular basis, thus forming a superior control loop of the building HVAC system. Thermal load metering of HVAC covers the heating and cooling demand measured at hydraulic distributor per each floor and building section. Further, active electric power of the following is measured: the total building active power (all three phases), chiller power and air handling unit (AHU) power. Regarding the IAQ, besides common zone temperature measurement, there are several IEQ sensors placed in the building which purvey information about not only temperature but also CO_2 concentration, relative humidity etc.

The 'EnergyFlex' service is also used to execute the testing sequence on the HVAC. The superior control algorithm takes control by sending "alive" commands to the BMS interface. The internet connection is secured by so-called 'watchdog' service in the 'Thingsboard'. The 'watchdog' signalizes to the BMS whenever the connection is lost enabeling fluent shift to the default control settings. Otherwise, the building HVAC is ready to be controlled from the cloud service when the testing sequence can be generated.

4 Testing sequence results

4.1 AHU demand response – response to step testing sequence

This test (see Fig. 4a) represents AHU demand response activated by the discontinuous (ON-OFF) control sequence. This particular test was executed during regular occupancy regime with feedback from CO2 monitoring. The CO_2 concentration was selected as constraint for the AHU flexibility events.

During the testing sequence, the AHU fan speed (setting of fan's frequency convertors) was set at following stages 0,70,25,80 and 0 % The 70 % stage represents regular operation. The drop to the 25 % stage represents the flexibility event activation. The 80% stage represents maximal fan speed in order to eliminate violation of the hygienic standards.

To satisfy the national hygienic standards (allowable limit of 1500 ppm, recommended 1000 ppm), the safety measure was introduced. When the CO_2 concentration reached 1300 ppm, the maximal possible fan speed (80% in this case) was automatically set.

As can be seen in Fig. 4, the power response to the control sequence was prompt and corresponds to the setpoint variation. The AHU power load was decreased about 4.9 kW till the CO_2 concentration level in the zone reached the safety margin, approx. 5 hours. Then the power load was increased about 6.6 kW during the rebound effect.

4.2 AHU demand response – response to modulated testing sequence

During this test (represented on Fig. 4b), the AHU demand response was activated by modular testing sequence. The AHUs were gradually modulated from 70 to 0 % and back to 70 % of their nominal capacity.

This test was executed out of working hours without occupancy to avoid hygienic standards violation during the test. Thus, the measured CO_2 concentration of indoor air, followed the concentration of the outdoor air.

The AHU power response followed immediately the modular control signal. The AHU power was gradually modulated in range from 6.84 kW to 0 kW.

4.3 Chiller demand response – response to step testing sequence

Testing sequence used during this test (Fig. 5 a) was conducted to characterize the chiller demand response to discontinuous control setting. The operation of the chiller was controlled indirectly by manipulating the chilled water temperature setpoint (leaving water temperature) by the predefined testing sequence. To provoke chiller to switch off, the temperature setpoint was suddenly increased from 9 to 20 °C for a predefined time period with consecutive decrease back to 9 °C.

The sudden temperature setpoint change resulted in approx. 5.5 h of chiller inactivity in the first case and approx. 4.5 h in the second case, before reaching the 20 °C chilled water setpoint and starting to cool again. The switching off the chiller was followed by almost immediate decrease of chiller power input. In our case by 11.1 kW in the first case and by 10.8 kW in the second case, resulting in steady total building power load profile without significant cycling caused by chiller operation. After decreasing the setpoint

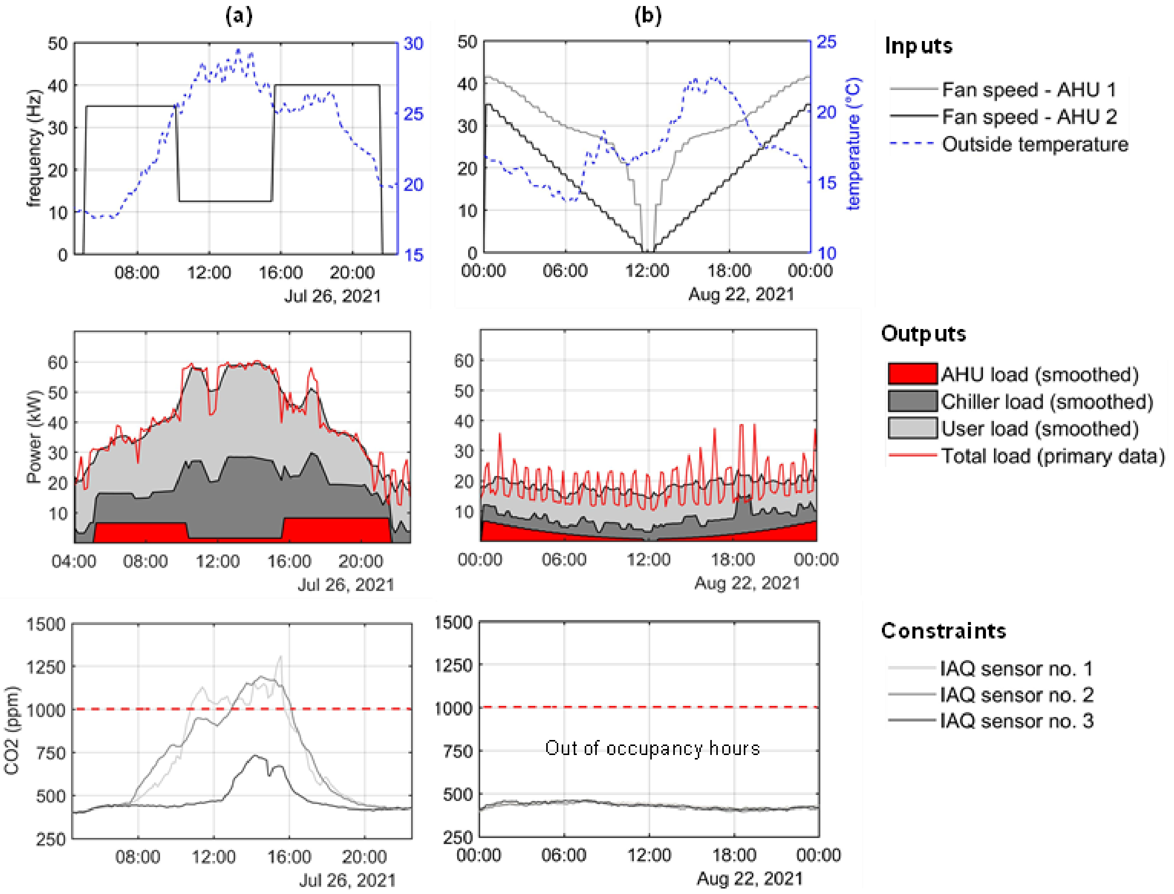

Fig. 4 Testing sequences provoking AHU's demand response

back to 9 °C. The significant increase of the power load at 28.4 kW can be observed, when the setpoints was set back to the original setting. The cooling water temperature followed the setpoints with minimal delay approx. 15 min.

The constrain for the chiller modulation was the indoor temperature and thermal comfort of the occupants. During these tests which were conducted during hot summer days, there was no violation of the indoor temperature in the zone with 25 °C zone temperature setpoint (setpoint no. 1). In case of the zone with temperature setpoint at 22 °C (setpoint no. 2), the indoor temperature exceeded the required temperature by 1 K during the chiller inactivity in first case (after 5.5 h) and by 1.4 K in second case (after 4.5 h).

4.4 Chiller demand response – response to modulated testing sequence

The conducted test presented in Fig. 5b shows the building response to modular control (modular testing sequence) of the chiller. Modular control was realized by gradual modulation of the chilled water temperature setpoint from 6 to 16 C during two summer weekend days based on the predefined testing sequence.

As can be seen in figure, the chilled water temperature was in line with the desired temperature setpoint and was modulated gradually. As can be also observed, the higher temperature setpoint correlates to chiller end electricity power consumption decrease during certain time period and otherwise. From the perspective of the power load reliability or predictability, despite the modular control of a chilled water temperature there can be observed significant fluctuation in the total building load profiles. These irregularities, with fluctuation in the range of 10 kW are given by the dual compressor construction of the studied chiller, specifically due to the cycling between operational stages. As observed, the given chiller is not able to provide modular demand response. The modulation is limited to the stages 0, 50, 100 % of its nominal capacity.

4.5 Chiller demand response – expected response to the real-time pricing

The final test presented in Fig. 6, was the most complex test, which tested building response to synthetic real time pricing profile during few weeks pilot operation, instead of short testing sequence. The modulation of the chiller as a dominant HVAC (and overall building) device was chosen for this test. During the test chilled water temperature setpoint was modulated based on the demand response rule-based algorithm, which was applied as a supervisory control. Based on the current energy price, the chiller temperature setpoint was modulated in a range of 6 to 16°C.

As can be seen from the figure, total building load increases and decreases in opposite to the course of a price signal due to demand-response operation of

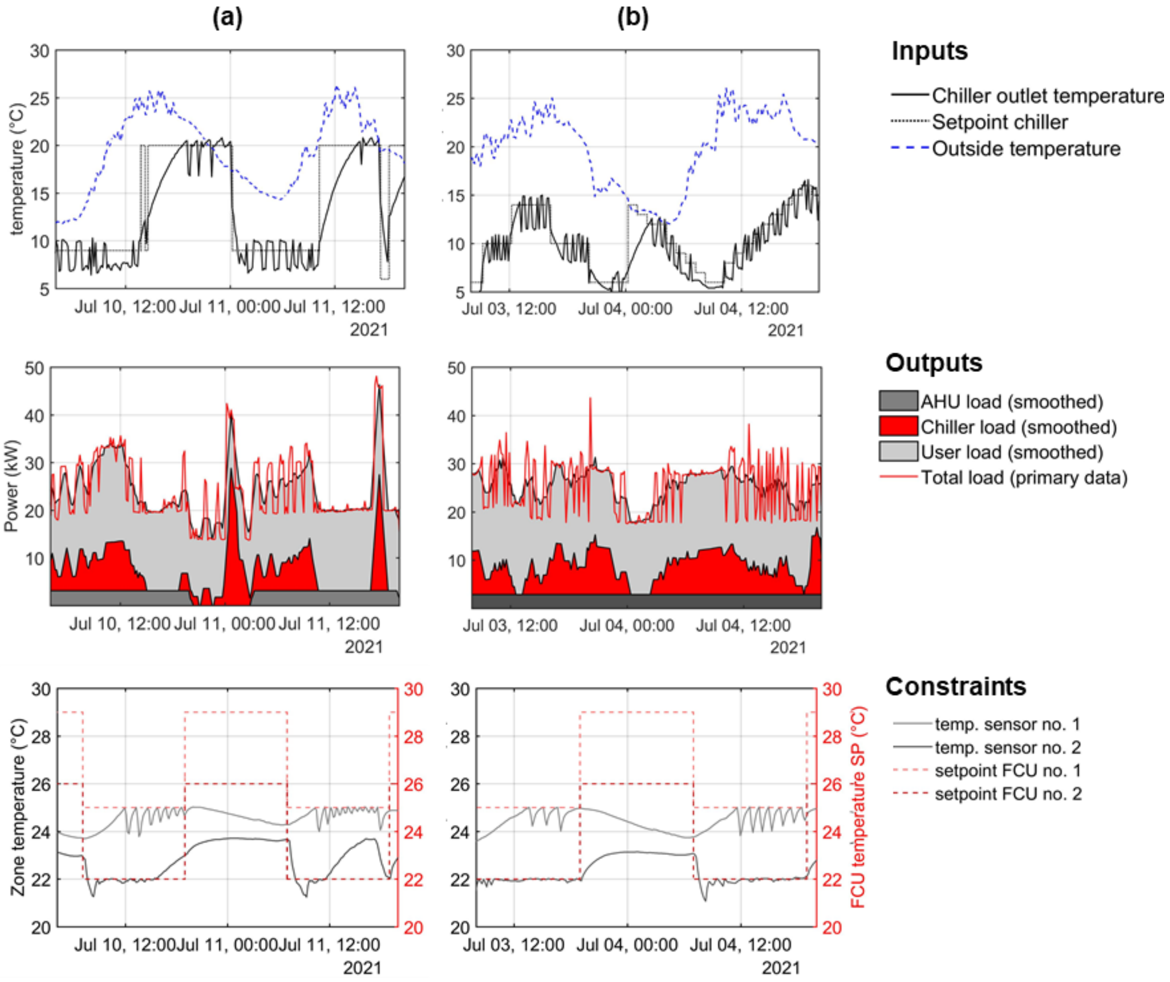

Fig. 5 Testing sequences provoking chiller's demand response

the chiller. However, due to chiller cycling, the peak power load often reaches the same values regardless of the value of a price signal or chilled water temperature setpoint, respectively.

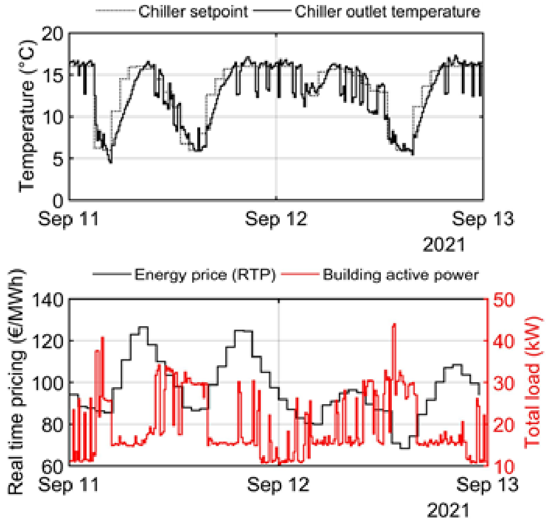

Fig. 6 Chiller demand response to real-time pricing signal

The internal temperature during this test (not plotted) was not significantly affected and followed the desired temperature with acceptable deviation. The rises of the chilled water temperature were sufficiently compensated by the existing thermal capacity of the storage tanks, the piping system and envelope.

5 Discussion

In the previous section, series of testing sequences were assessed to investigate the authentic demand response of the specific building. Although the results of these experiments cannot be entirely generalized, they indicate some important characteristics of the building flexibility, that might be shared with similar type of buildings and HVAC systems. The results are further discussed with respect of the proposed testing routine.

In terms of impact to IEQ and level of occupant's acceptance, the testing sequences did not cause significant disturbances to the thermal comfort and IAQ. The demand of the HVAC systems was reduced in the range of 2-5 hours with acceptable disturbance to the indoor environment. The demand shift is accounted mainly to thermal inertia of the water storage tanks, volume of piping system and building construction mass. The indoor environment satisfied relevant standard (e.g. EN-16798) during the presented tests. It should be noted, that in extreme weather conditions or at maximum occupancy, the impact of the SG adaptation may increase the overheating risk or air quality discomfort. The IEQ feedback to the aggregator support service or overrule function at local control is recommended, to enable consideration of the occupant's comfort. It can be generally stated, that, the level of acceptance is relatively high, unless the change in the indoor environment is not rapid (e.g. FCU demand control). Our experience is that, the building demand response could be realized in synergy with occupant's requirements.

To recall, the presented routine mainly consists of 'step' and 'modular' testing sequences acting at AHUs and chiller. The experiments revealed the building capability to shed the AHU system's load about 4.9 kW (6.8 kW, if unit is completely switched off) for 5 hours, while still satisfying IEQ standards. Similarly for chiller, the capability to shed the load was found around 10 kW for period in range of 4.5 to 5.5 hours depending on the type of experiment. The resulted flexible energy can be estimated in range of 72 to 84 kWh per event. These numbers correspond to previous research [10] done for family houses in Belgium, where median flexible capacity trigged by changing zone setpoints over a 2h period differ from 13 to 18 kWh.

While the quantity of the flexible energy is in line with the previous research, the quality of the responded power profile (as characteristic) is rarely discussed. The total building demand, provoked by either 'step' or 'modular' testing sequence, was found very irregular. The fluctuation is mainly driven by the chiller with two-compressor configuration. Partially it is also generated by user's and auxiliary (e.g. lighting) building demand. The quality of the power demand is questionable, especially if the building flexibility should have provided reliable and predictable ramping of the profile. The modulation of the power profile has certain limits which are discussed hereunder.

Although the AHU power demand (itself) can respond fairly well to the modular testing sequence, the quality of the overall building profile is minimally affected. Moreover, utilizing only part of the nominal flow rate may disturb the pressure settings in the ventilation system. For part-load fan speed settings, the supply air in the ventilation system may be distributed unevenly to the supply elements (FCUs). The part-load operation may introduce risk of IAQ discomfort or even lead to exceeding hygiene criteria locally in some zones.

This specific type of chiller due to the previously mentioned construction issue is not capable to provide reasonable ramping respond to the modular testing sequence. Better respond could be expected from modern chillers with inverter compressor technology. However, the commonly embedded controller of these devices may still lead to the stage control accompanying by the cycling between stages as presented in this study (especially when the cascade of chillers is present). Other issue to state is relatively large weather-dependence of chiller's power demand, that makes the modulation even more challenging. To summarize, the profile modulation at the building level does not seem to be effective, reliable and easy-to-predict, unless the device and its control would be specifically optimized for that purpose.

The 'step' testing sequence led always to switching off the devices for a certain period of time. From the perspective of aggregator, this type of activation may offer more reliable and predictable outcome within the given time resolution of day-a-head markets (15 to 60 min). In addition, the 'step' testing sequence mostly provoke the maximal possible power reduction (about 16 kW for 5 hours) representing 29 % of the total peak load (assuming peak load at 55 kW). This amount is measurable by common power meters. Thus, the observability of the activated load and further settlement between aggregator and building operator/owner may be improved by using stage control.

In any case, the single building demand represents very minor part of the minimum tradable volume, that is typically 1 MW. The aggregation is absolutely necessary to enter the wholesale or short-term energy market with building energy simulation. Based on the studied case, the aggregated building cluster should reach size in terms of hundreds similar buildings.

The main limitation of this experimental flexibility characterization is case dependency on given system and also testing period with various weather conditions and level of occupancy. The presented experimental results represent rather nominal value neglecting the whole-year operation. Moreover, the calculation of most of the flexibility metric in experimental studies is complicated due to difficulty in estimating baseline definition at the single building level. Therefore, the building energy simulation tool are currently being exploited. The testing routine will be executed on the validated model to complete the characterization of the flexibility.

6 Conclusion

This paper introduced experimental testing routine to characterize building energy flexibility. The routine addressed a possible procedure to be done prior adding a given building to a larger aggregated portfolio. The procedure aimed to align requirements and expectations of main actors: building flexibility aggregators, building owner/operators and occupants via several audits and tests. The procedure was mainly built on testing sequences, specifically 'step' and 'modular' testing sequences were utilized and demonstrated on the real mid-size office building in Prague. The testing control sequences were sent to the BMS via newly developed cloud-based service supporting the building aggregation. The testing sequences provoked authentic demand response measured and stored for the flexibility characterization. The monitoring was not only limited to power metering but includes also IEQ, HVAC system and meteorological monitoring. The tests were successfully executed on AHUs and the chiller and their flexibility potential was evaluated.

To conclude the key findings, 1) the operation of the HVAC system can be blocked or limited for relatively long period of time, (range of 2 to 5 hours in the studied cases) without any critical consequences to indoor environment quality. 2) approximately 30 % of the total power per testing event can be considered as flexible, however the long-term flexibility potential must be further investigated using simulation tools. 3) The quality of the power profile was found highly irregular. Due to the power profile fluctuation the ramping/modulation at the single building level was not found effective. The multi-stage control causing detectable power reduction can be recommended. This type of control provoked more observable, reliable, and easy-to-predict demand response.

The flexibility characterization will be extended for the whole-year performance in the following research, where the building energy simulation tools are being exploited. The testing sequences will be applied again to the validated simulation model.

7 Abbreviations

AHU	Air Handling Unit
API	Application Programming Interface
BMS	Building Management System
DSO	Distribution System Operator
HVAC	Heating, Ventilation, Air-Conditioning
IAQ	Indoor Air Quality
IEQ	Indoor Environment Quality
PLC	Programmable Logic Controller
SG	Smart Grid
TSO	Transmission System Operator

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