Energy & Buildings 316 (2024) 114321

Contents lists available at ScienceDirect

Energy & Buildings

journal homepage: www.elsevier.com/locate/enb

Demonstrating the load-shifting potential of a schedule-based control in a real-life educational building

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ARTICLE INFO

Keywords:
Energy flexibility
Demand side flexibility
Heating control
School buildings
Practical challenges

ABSTRACT

This work investigates the potential of simplified control approaches to deploy the building energy flexibility (BEF), here for the shifting of the space-heating load in a real-life educational building. The educational building is a passive house school where internal gains play an important role in the room thermal dynamics. It is equipped with a waterborne heat distribution system connected to district heating. The building is located in Elverum, Norway, having a strong heating-dominated climate. Focusing on schedule-based control strategies for pre-heating the building in the mornings, the study demonstrates significant load shifting to off-peak hours. The energy use during typical peak hours (7a.m. to 9a.m.) is reduced by 50% while the daily energy use is not increased significantly, highlighting the effectiveness of this simple approach. Occupant acceptance surveys among the pupils reveal no significant differences in thermal comfort perception between the periods with business-as-usual and schedule-based controls. Practical challenges in integrating simplified controls are highlighted and underscore the importance of considering energy flexibility during the building tendering and design phase. Bridging the gap between theoretical research and real-life applications, this research contributes to the advancement of energy-flexible operation of real-life buildings.

1. Introduction

1.1. Background information

Buildings, accounting for about 40 % of total primary energy consumption in Europe, are a significant asset for participating in demand response (DR) and providing energy flexibility [1]. Deploying the building energy flexibility (BEF) will be crucial for the stability of the electricity grid with the increasing penetration of variable renewable energy sources [2]. However, BEF is not only limited to the electricity grid, but allows also for a more flexible operation of thermal grids [3]. BEF can be understood as the margin in which a building can be operated while still fulfilling its functional requirements [4]. While for electricity grids the focus on energy flexibility mainly stems from the integration of intermittent renewable energy source, the potential benefits for thermal grids with regards to energy flexibility are additionally in the possibility to use surplus heat [5] and increased security of being able to deliver heat to the consumers at the end of the (district) heating grid during peak demand periods. Building heating systems are one possible asset that allows to deploy the BEF by applying dedicated control strategies.

In recent years, the pursuit of energy efficiency and cost-effectiveness in building operations has led to the exploration of advanced control strategies. Among these strategies, model-predictive control (MPC) has emerged as a promising approach, demonstrating substantial improvements in operational costs [6]. However, despite the potential benefits regarding thermal comfort improvement [7], operational costs or energy use [8,9], practical implementation in real buildings remains a formidable challenge, with existing research primarily confined to simulation studies [10]. Zacekova et al. [11] show that the identification of a control-oriented model for an MPC is already a delicate task in a simulation environment, but is even more complicated for a real-life implementation due to accompanying issues such as real-operation data acquisition, and processing. Kim argues that a greater acceptance of advanced controls for building operation can be achieved mainly by demonstrating these solutions in real-life buildings [12]. Blum et al. [13] implement an MPC for heating, ventilation and air-conditioning (HVAC) systems into an office building and point out that, among others, data collection and implementation preparation can require as much effort as the model development and integration. Clauß et al. [14] outlined and categorized numerous practical challenges for

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https://doi.org/10.1016/j.enbuild.2024.114321
Received 28 February 2024; Received in revised form 16 April 2024; Accepted 20 May 2024

Nomenclature

BAU	Business as usual
BEF	Building energy flexibility
BMS	Building management system
DE	Delivered energy
DR	Demand response
ES	Energy stress
FME ZEN	Research Centre on Zero Emission Neighbourhoods in Smart Cities
HDD	Heating degree day
HDH	Heating degree hour
KPI	Key performance indicator
MPC	Model-predictive control
PL	Peak load
TSV	Thermal sensation vote
$E_{\mathrm{del,d}}$	Daily delivered energy
$E_{\mathrm{del,7-9\ a.m.,d}}$	Delivered energy between 7 a.m. and 9 a.m. of a day
P_{h}	Hourly peak load
T_{b}	Base temperature
$\overline{T_{\mathrm{o,d}}}$	Mean daily outdoor temperature
$\overline{T_{\mathrm{o,h}}}$	Mean hourly outdoor temperature

the implementation of data-driven predictive control for the operation of commercial buildings showing that several of the experienced challenges during the operational phase are rooted in the tendering, design and construction phase of a building project.

The readiness of buildings and their systems to effectively execute controls targeting load shifting has become a critical area of investigation. Buildings are not yet ready to seamlessly integrate advanced controls [15]. To bridge this gap and expedite the adoption of strategies that leverage BEF, simplified control approaches can be considered as an initial step towards a more widespread deployment of advanced BEF controls. Building upon this premise, recent studies by Amato et al. [16] inspired by MPC principles, and Clauß et al. [17] advocating for schedule-based control, have demonstrated that such simplified controls utilizing BEF can significantly enhance load shifting in existing buildings. With simplified controls the authors refer to rule-based control strategies that do not involve solving a numerical optimization problem (and identify a control-oriented model) as part of the control framework. These simplified controls offer a pragmatic solution, making implementation more accessible while capitalizing on the inherent flexibility within building systems. Similar recommendations are presented in a recent study by de Chalendar et al. [18] outlining the role of energy flexibility of commercial buildings in the energy transition. The study of Amato et al. implemented room temperature set-point changes with a trajectory that mimics a typical behaviour of a real economic MPC. They show that this approach can achieve load shifting of the heating energy use. Furthermore, they show that the extent to which load shifting could be achieved was limited by the hydronics of the radiator system.

While simplified control proved to be effective in residential buildings, the picture regarding non-residential buildings is not clear even though simple controllers could be an interesting alternative to the complexity of MPC. For instance, Merema et al. [19] demonstrated that variable occupancy and internal gains played a major role in the thermal dynamics of highly insulated educational buildings. To address this challenge, they developed and tested a complex MPC framework. Thilker et al. [20] developed a non-linear grey-box model in to control the hydronic space-heating system of a building, taking a school as a test case. Although their results are encouraging, they demonstrate that the implementation of MPC for buildings with hydronic heating is not a straightforward task and requires high-level modelling skills. For the evaluation of the efficiency of the implemented control strategy, that control is usually compared to a simulated business-as-usual (BAU). Bird et al. [21] demonstrate a real-world implementation of a cloud-based MPC setup, comparing the energy use during MPC operation with a simulated BAU operation. Freund and Schmitz [22] implement a MPC in an office building with several heating circuits comparing the circuit with MPC operation to the other circuits that operate BAU. This approach however assumes that all heating circuits behave similar, something which is highly unlikely in real-building operation. Non-residential buildings can have various purposes thus having different requirements on technical systems and energy use patterns. Internal heat gains are often more important in non-residential buildings, especially in classrooms with high levels of occupancy. This makes the room thermal dynamics more complex due to more disturbances. However, in non-residential buildings, compared to residential buildings, building management systems (BMS) and building automation systems are highly important for continuously deploying the BEF potential [1] of the space heating system by implementing room temperature set-point changes [23]. However, BMSs rarely support the option of frequent setpoint changes neither on room nor heat distribution system level.

1.2. Main contribution and scope of the study

This work demonstrates on the practical implementation of simplified controls to deploy the BEF for load shifting within educational buildings with water-borne heating systems and connected to a district heating grid. The main contributions of this study lie in addressing the challenges associated with transitioning from simulation studies to real-world applications. The study focuses on an existing educational building equipped with a standard variable-air volume (VAV) mechanical ventilation and hydronic heating systems. Rule-based control strategies are investigated as tangible solutions to deploy the space-heating BEF and to contribute to sustainable building practices. The controller is applied, and its performance monitored over a period of six weeks. The paper answers to three original research questions:

- RQ1: *How can simplified control approaches leverage building space-heating flexibility to enhance load shifting in educational buildings?*

This question delves into the development and application of rule-based control strategies. The study aims to explore the effectiveness of simplified controls in buildings, drawing inspiration from successful approaches demonstrated by Amato et al. [16] and Clauß et al. [17] for residential buildings. The focus is on practicality and accessibility of the controls to be implemented, with an emphasis on the inherent flexibility within building systems. Given its relative simplicity, a major risk for rule-based controls is to significantly increase the energy use to activate energy flexibility. The goal is to demonstrate that both objectives can be reached simultaneously with a simple controller.

- RQ2: *How do occupants perceive changes in indoor climate and building operation when deploying the BEF in educational buildings?*

Recognizing the importance of user experience in the real-world adoption of advanced control strategies, this question addresses the aspect of user acceptance of strategies that aim to deploy the BEF. Through a simple feedback mechanism the study aims to gauge user acceptance, understanding how changes in indoor climate and building operation influence occupants. This research question aligns with the broader objective of knowledge transfer from research to practice by involving industrial players and ensuring that the implemented solutions align with user expectations and comfort levels.

- RQ3: *What practical challenges exist in integrating simplified control approaches, designed to deploy building energy flexibility, into existing building and BMS?*

This question elaborates on the process of implementing rule-based control strategies into the existing infrastructure of educational buildings. The study identifies the practical challenges associated with seamlessly integrating these controls into BMS, recognizing that BMS plays a pivotal role in the continuous deployment of building energy flexibility. The investigation encompasses aspects such as data acquisition, and processing constraints. Addressing these challenges is crucial for the successful and practical application of building energy flexibility on a broader scale within non-residential buildings.

RBC is the dominant type of control in buildings. However, to the authors‘ knowledge, a limited number of studies have investigated the use of RBC in real-life buildings in the context of peak load reduction using the building thermal mass as energy storage. It should still be proved that such a simple control can provide a significant reduction of energy use during peak hours without charging the building thermal mass extensively in a way that would compromise energy efficiency. This study seeks to bridge the gap between theoretical research and practical solutions in the realm of building operations. By addressing the three research questions, the work contributes to the development of scalable, real-world applications of space-heating BEF in educational buildings, offering insights into demand side flexibility (pre-heating of the building), key performance indicators (KPIs), and user acceptance that can be applied to a broader context, including large property portfolios for municipalities and commercial building owners.

The paper is organized as follows: Section 2 provides an overview of the methodology and a detailed description of the building and its heating system. Results are presented and discussed in Section 3 while Section 4 concludes on the work.

2. Methodology and test case

The experiments consist in changing the room set-point temperature while the performance is evaluated using i) the resulting response of the room temperature and ii) a simple survey among pupils to document their perceived thermal comfort. For detailed information on the case study building, the experiment and the data collection see Sections 2.1, 2.2 and 2.3 respectively.

A widespread implementation for controls that deploy the energy flexibility potential of buildings will only be achieved if building occupants accept the resulting changes in the indoor thermal environment. The perceived indoor thermal comfort is tracked throughout the experiments. To that end, a simple survey is executed together with the experiments on the setpoint changes to receive feedback from pupils. The survey is introduced in Section 2.3.

The experiments are executed over a 6-week period from 13.11.2023 to 24.12.2023 (in the remainder of this article called “experimental period”) using an alternating weekly pattern, i.e., one week in which the setpoints are adjusted (“test”) is followed by a week with no setpoint adjustments (“business as usual”, BAU). Consequently, the three test-weeks are referred to as “test-period”, and the three BAU-weeks as “BAU-period” in the following. The purpose of this alternating pattern is to study the impact of the setpoint adjustments on the selected KPI compared to the reference case without setpoint adjustments under similar weather conditions. The alternating pattern also allows to compare the “test period” with a measured reference compared to most other studies which compare “test periods” with a simulated reference. The experiments are performed in the middle of the heating season at times with low solar radiation to test and verify the potential for load shifting during periods with high heating demand and minimum disturbance from solar radiation. Room indoor air temperature set-point changes are implemented via a schedule in the BMS of the school. Changing these set-points aims to provide a load shift from typical peak load periods in the local heating grid to off-peak periods directly preceding the peak load hours. Increasing indoor air temperature set points during the off-peak hours will accumulate thermal energy in the thermal mass of the building to bridge the succeeding peak-hours in which the operation of the heating system then can be delayed significantly. Set-point changes are inferred for all rooms of the school building.

In Norway, the price scheme for district heating depends on the district heating provider. Often, the total cost for district heating consists of several prices: energy price, peak demand price and a bonus for a high temperature difference between supply and return on the primary side. Per today, district heating in Norway typically has a flat energy price signal where prices do not vary on an hourly basis. However, it can be assumed that demand patterns for district heating and electricity are similar and thus both, district heating and electricity, have peak load periods during comparable hours. Typical district heating demand profiles for space heating and hot water peak between 6 a.m. to 9 a.m. in Norway [24]. Regarding electricity demand patterns, a typical high-price (peak load) period in Norway appears in the morning from about 7 a.m. to 9 a.m. The second typical high-price (peak-load) period is in the late afternoon when people get home from work [25].

2.1. *Case study building*

The building used as a case in this study is a school in the “Ydalir” Zero Emission Neighbourhood in the Norwegian city of Elverum. While the neighbourhood will, upon completion in 2030, comprise between 800 and 1000 residential units, the kindergarten and school were already opened in autumn 2019. Ydalir is a pilot area in the Research Centre on Zero Emission Neighbourhoods in Smart Cities (FME ZEN, https://fmezen.no/) and serves as a demonstration area for real-life testing of solutions towards a net-zero emission balance over its life cycle. The school (Fig. 1) has a gross floor area of approximately 6,500 m^2 and is designed for 350 pupils from 6 to16 years of age.

The school fulfils Norwegian passive house requirements according to standard NS 3701:2012 [26]. Regarding the building envelope, the following U-values are reached [27]: external walls exposed to outdoor air 0.13 W/m^2K, external walls towards ground 0.18 W/m^2K, roof 0.08 W/m^2K, floor exposed to outdoor air 0.16 W/m^2K, and floor towards ground 0.12 W/m^2K. Moreover, the standard’s requirements for the average U-value of windows and doors of 0.8 W/m^2K, the thermal bridge factor (max. 0.3 W/m^2K) and normalised air leakage at 50 Pa pressure difference (n_{50}) of 0.6 h^{-1} are satisfied. The school’s net energy demand is designed as 26.3 kWh/m^2a according to NS 3701:2012.

For the school’s load bearing structure, glued laminated timber was used except for the floor and external walls towards the ground, for which concrete was used.

The school is connected to the local district heating grid. Its heating system is water-based with radiators in all rooms except for the sports hall’s dressing rooms which have underfloor heating. Radiator supply temperatures are approximately 55 °C to 60 °C throughout the experimental period. The supply temperature is outdoor temperature-compensated. Within the radiator circuit, the radiators are installed in parallel. All rooms are connected to a VAV mechanical ventilation system, where the supply air flow rates are primarily controlled by a time schedule, but also consider room CO_2 levels and room temperatures. The design values for supply air volume flow rates are based on the Norwegian building code which was valid during the design phase of the school, TEK 10 [28]. A typical supply air temperature is between 19.5 °C and 20.5 °C. A schematic of the system is presented in Fig. 2.

2.2. *Experiments*

The experiments are executed over a 6-week period from 13.11.2023 to 24.12.2023. The outdoor air temperature and global horizontal radiation in the city of Elverum during the experimental period are shown in Fig. 3. Since the city of Elverum does not have an official weather station, the Open-Meteo Historical Weather API [29] which uses the fifth-generation European Centre for Medium-Range Weather Forecasts reanalysis model as data source is used. From this data, the average outdoor air temperature for the experimental period is −8.4 °C, for the

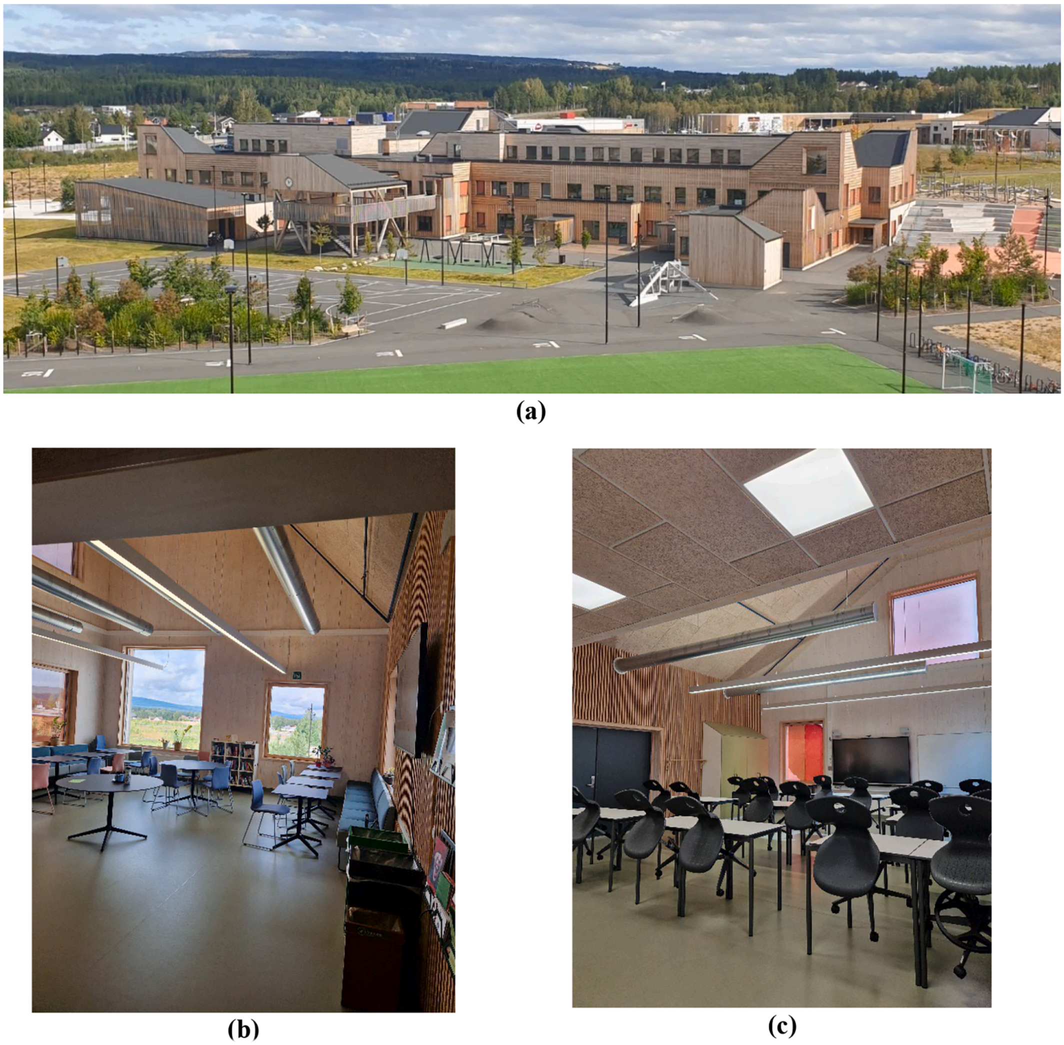


Fig. 1. Photo of a) Ydalir school from 2021 viewed from the southwest, © Daniela Baer, b) teachers' room (2.001) towards northwest/southwest and c) classroom (1.084) towards southeast/southwest.

test period it is −8.7 °C, and for the BAU period it is −8.1 °C. The average daily solar irradiation on a horizontal surface during the entire experimental period, the test period, and the BAU period, is 222 W/m^2, 250 W/m^2, and 194 W/m^2.

To that end, a schedule to adjust the room air temperature setpoints is introduced to the BMS aiming to avoid heating during the peak-load period between 7 a.m. to 9 a.m. As visualized in Fig. 4, these setpoints are increased by 2 K between 4 a.m. and 7 a.m., then reduced by 1 K until 12p.m., before going back to the original setpoint temperature until the next day. Initially, the individual rooms of the schools have different air temperature set-points for heating which typically range between 20 °C and 22 °C apart from some technical or cleaning rooms. By implementing the setpoint changes as increase and decrease compared to the reference (BAU) set-point, it is accounted for the different individual temperature preferences in each of the rooms. It is pointed out here that a setpoint change at 4 a.m. is not based on any model but is based on the experience of the facility manager. The range of temperature change of + 2 K and −1 K is in line with EN15251:2007 [30] stating that a minimum and maximum indoor operative temperature of 20 °C and 24 °C correspond to a predicted percentage dissatisfied (PPD) < 10 %.

There are several studies where increasing the room temperature setpoints goes hand in hand with increasing the radiator supply temperature. However, from a practical point of view, it is not a necessity to also increase the radiator supply temperature because it depends on the prevailing settings of the heat distribution system whether the current radiator supply temperature is sufficiently high to support room temperature setpoint changes. The heating capacity in the heat distribution system depends on the flow rates in the system and on the radiator supply temperature set by the weather compensation curve. In this work, the supply water temperature defined by the weather compensation curve is deemed high enough to be able to raise room temperatures to the desired set-points within a period of three hours (i.e., from 4 a.m. to 7 a.m.). This choice is taken in collaboration with the facility manager of the building based on his experience for operating the system.

As part of the experiments, a simple user feedback survey is answered every morning at the beginning of the school day. Alternating the heating pattern every week of the experiments allows for investigating whether pupils report a difference in the perceived thermal comfort. The pupils are not informed whether the pre-heating of the rooms is applied during some of the weeks.

2.3. Instrumentation and data collection methods

2.3.1. Technical system

Data for room air temperature, room ventilation air flow rates, and room radiator valve positions are collected via the BMS with a 0.01 °C,

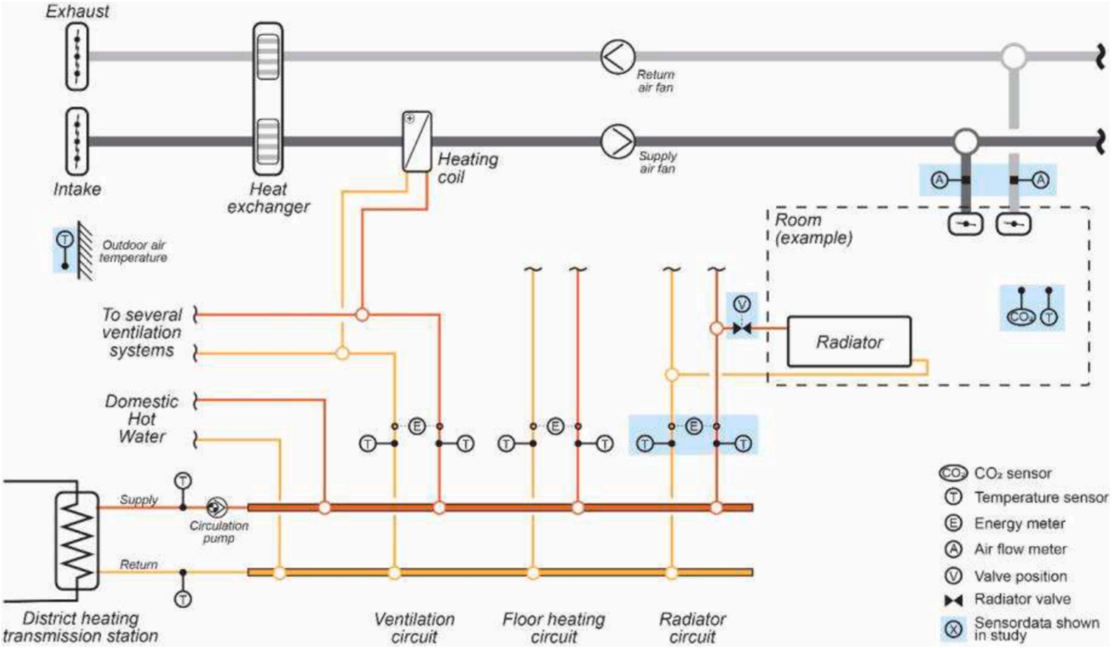


Fig. 2. Schematic of the heat distribution system of Ydalir School.

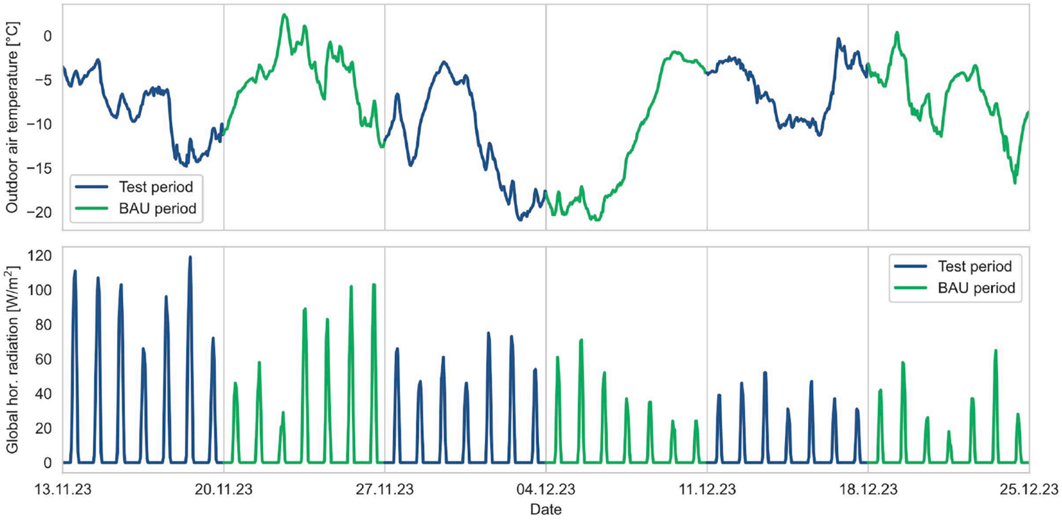
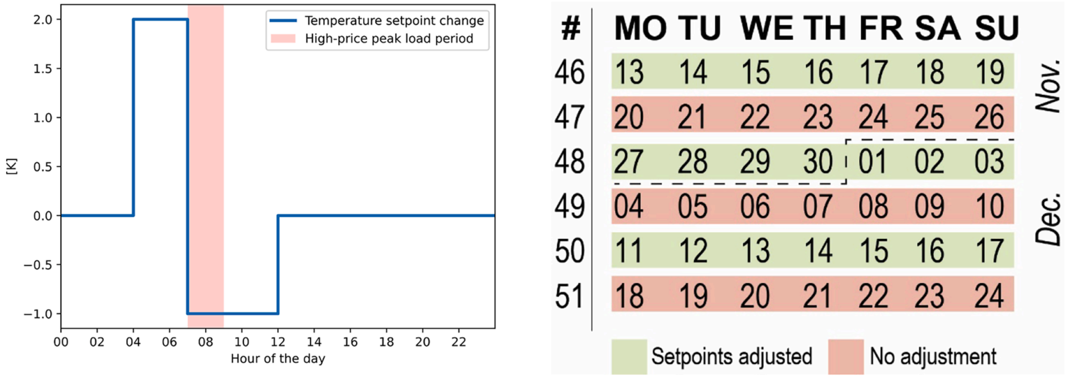


Fig. 3. Outdoor air temperature and global horizontal radiation in the city of Elverum during the experimental period. The weeks of the test period are shown in blue, while the weeks of the BAU period are shown in green. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)



#	MO	TU	WE	TH	FR	SA	SU
46	13	14	15	16	17	18	19
47	20	21	22	23	24	25	26
48	27	28	29	30	01	02	03
49	04	05	06	07	08	09	10
50	11	12	13	14	15	16	17
51	18	19	20	21	22	23	24

🟩 Setpoints adjusted 🟥 No adjustment

Fig. 4. Schematic illustration of room air temperature setpoint changes and bi-weekly test design schedule.

0.01 m^3/h and 1 % resolution, respectively. Energy meters record thermal energy supplied to the radiator, underfloor heating, and ventilation system circuits with a 1-kWh resolution with a 15-minutes resolution in an energy management system.

2.3.2. Room temperature measurements

Set-point changes are inferred for all rooms of the school building, whereas the analysis of the indoor temperature dynamics is based on nine rooms that were deemed representative and that were chosen in collaboration with the school's principle and facility manager. This was necessary due to restrictions in the BMS which logs historical measurement data only if requested by the user and due to storage capacity restrictions by the provider of the BMS. Hence, one room per floor and façade direction was chosen. Fig. 5 shows a floor plan of the school highlighting the nine rooms used for the evaluation.

2.3.3. Survey

User acceptance is evaluated based on a short and simple survey in the beginning of each school day throughout the 6-week test period. At around 8:00–9:00 each morning, the teacher asks the pupils to raise their hands as feedback to three simple questions about the thermal indoor environment: "Do you feel too cold – comfortable – or too warm?". Raised hands are then counted by the teacher and noted in a form as shown exemplary in Table 1 (the original form is in Norwegian). The user feedback form is kept very simple and short by intention, considering the partially young age of pupils and using as little time as possible every morning. Recording the feedback in the early morning every school day covers the time in which the effect of the setpoint changes is most apparent. However, it has to be kept in mind that pupils walking or biking to the school in the morning will have a higher metabolic rate upon arrival at the classroom and may perceive the indoor environment with increased indoor temperature as too warm. This is because they have not yet adapted to the change of environment (cold winter outdoor conditions vs. heated indoor environment) and metabolic rate (e.g., biking vs. sitting) [31,32]. After arrival, the room is in free-floating mode during the test leading to a transient indoor thermal environment with decreasing temperature. These temperature drifts can also generate thermal discomfort [33]. However, this effect is not investigated as the survey is performed prior to the temperature decay.

Table 1
Example form for recording the pupils' feedback on the perceived (thermal) indoor climate conditions (original was in Norwegian).

Date	Time	Class	Room	Thermal comfort (# of pupils raising hands)		
				Too cold	Comfortable	Too warm
07.12.23 …	08:17	5b	1.084	5	12	7

2.4. Key performance indicators related to energy flexibility

The load shifting potential is evaluated i) quantitatively by using several KPIs and ii) qualitatively by investigating the room temperature trends, more specifically the room temperatures' decrease after the preheating events and for how long the operation of the room heating can be extended after the load shifting event. It is here pointed out that the actual room temperature decrease over time is not only dependent on the building insulation level but also influenced by the operational settings for the technical systems. The applied KPIs are presented in Table 2.

Regarding the survey, the difference in the perceived thermal comfort is compared qualitatively and quantitatively based on the reported thermal sensation votes.

The KPIs are calculated from the following equations. Eq. (1) shows DE as the sum of daily delivered energy to the radiator circuit ($E_{\mathrm{del,d}}$) over all n days of either the test or the BAU period. The second KPI DE_{norm} is calculated from dividing DE by the number of heating degree days (HDD), calculated from Eq. (2) according to NS-EN ISO 15927–6:2007 [35]. It represents the accumulated daily temperature difference between a defined base temperature T_{b}, in Norway usually taken as 17 °C, and is the average daily outdoor temperature $\overline{T_{\mathrm{o,d}}}$ over all days of test and BAU period, respectively.

The third KPI, energy stress ES, is calculated from Eq. (3), where only delivered energy to the radiator circuit between 7 a.m. and 9 a.m. of every day of the respective operation, test or BAU, is considered. The normalized energy stress ES_{norm} is obtained from dividing ES by the number of heating degree hours (HDH), according to NS-EN ISO 15927–6:2007 (Eq. (4). Similar to the HDD, HDH are the accumulated temperature difference between the base temperature T_{b} and the average hourly outdoor temperature $\overline{T_{\mathrm{o,h}}}$. Again, T_{b} is taken as 17 °C. It should be noted that, for calculating ES_{norm}, HDH are taken as the

Fig. 5. Floor plan for 1st floor (left) and 2nd floor (right) of Ydalir School with the representative rooms highlighted in blue. Measurement data is logged in the representative rooms only. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 2
Overview of key performance indicators (KPI) applied in this study.

#	*KPI*	*Description*	*Unit*
1	*DE*	The KPI *Delivered Energy* (*DE*) considers the sum of daily delivered energy to the radiator circuit during over all days of the test period with applied setpoint changes (DE_{test}) or the BAU case (DE_{BAU}) in absolute numbers.	[kWh]
2	DE_{norm}	The KPI *Normalized Delivered Energy* ($DE_{\text{norm.}}$) represents the KPIs DE_{test} and DE_{BAU} normalized by the sum heating degree days (HDD) during the respective periods ($DE_{\text{norm,test}}$ and $DE_{\text{norm,BAU}}$).	[kWh/ Kd]
3	*ES*	The KPI *Energy stress* (*ES*) indicates the sum of energy delivered to the radiator circuit from 7 to 9 a.m. (defined according to [34]) of each day either of the test period with applied setpoint changes (ES_{test}) or the BAU case (ES_{BAU}) in absolute numbers.	[kWh]
4	ES_{norm}	The KPI *Normalized Energy Stress* ($ES_{\text{norm.}}$) represents the KPIs ES_{test} and ES_{BAU} normalized by the sum heating degree hours (HDH) from 7 to 9 a.m. (according to [34]) for the test ($ES_{\text{norm,test}}$) and the BAU period ($ES_{\text{norm,BAU}}$), respectively.	[kWh/ Kh]
5	*PL*	The KPI *Peak Load* (*PL*) refers to the maximum hourly peak load for the radiator circuit during the test period with applied setpoint changes (PL_{test}) and the BAU case (PL_{BAU}) in absolute numbers.	[kW]
6	PL_{norm}	The KPI *Normalized Peak Load* (PL_{norm}) represents the KPIs PL_{test} and PL_{BAU} normalized by the sum heating degree hours (HDH) at the time the peak occurs for the test ($PL_{\text{norm,test}}$) and the BAU period ($PL_{\text{norm,BAU}}$), respectively.	[kW/ Kh]

accumulated temperature difference between T_{b} and the average hourly outdoor temperature between 7 a.m. and 9 a.m. of the test and BAU period, respectively.

The fifth KPI, peak load *PL*, is obtained from Eq. (5) and represents the maximum value of delivered energy in kilowatt-hours to the radiator circuit within one hour P_{h} of the test and BAU period, respectively. Again, the normalized peak load PL_{norm}, is calculated from dividing *PL* by the HDH at the point in time $\max(P_{\text{h}})$ occurs, i.e., for one hour only.

$$DE = \sum_{d=1}^{n} E_{del,d} \tag{1}$$

$$HDD = \sum_{d=1}^{n} \left(T_{\text{b}} - \overline{T_{\text{o,d}}}\right) \tag{2}$$

$$ES = \sum_{d=1}^{n} E_{\text{del,7}-9\text{ a.m.,d}} \tag{3}$$

$$HDH = \sum_{h=1}^{n} \left(T_{\text{b}} - \overline{T_{\text{o,h}}}\right) \tag{4}$$

$$PL = \max(P_{\text{h}}) \tag{5}$$

3. Results and discussion

In this section, the experimental results are analysed qualitatively (Fig. 6 to Fig. 8) for exemplary rooms and quantitatively for all rooms connected to the radiator circuit (Table 3). In relation to the technical experiment, the survey is analysed comparing the feedback (average vote) for periods with and without setpoint changes. Practical challenges of the study are presented and discussed at the end of this section.

3.1. *Load shifting potential*

For a qualitative analysis, Fig. 6 to Fig. 8 illustrate the thermal behaviour of exemplary rooms, where i) Fig. 6 is used to show the daily patterns for two exemplary rooms for the whole test period, ii) Fig. 7 to present in more detail how the operation of the heating and ventilation system during a typical day with BAU operation and load shifting operation influence the room temperature and iii) Fig. 8 to compare the thermal behaviour of several classrooms.

Fig. 6 shows the hourly patterns for all weekdays for test periods (blue) and BAU periods (green) for room 1017 (library) and room 1084 (classroom). During BAU operation, room temperatures are thermostat-controlled with a heating setpoint of 21 °C and a deadband of ± 0.5C, hence the “swinging” patterns. For the classroom, slightly larger variations in indoor temperature are visible, especially around noon of nearly all days during the experimental period which can be attributed to the presence of pupils. Regarding the load shifting operation (blue), the simple schedule is able to increase room temperatures based on a schedule and thus to move loads from peak to off-peak hours. The library behaves as expected with the measured room temperature following the heating setpoint well. The room shows the same behaviour for all working days having an increase in the room temperature up to 7 a.m. The pre-heating period is just long enough to increase the room temperature to 23 °C before 7 a.m. Starting at 7 a.m. the room cools down to 21 °C up until 12p.m. showing a gradually decreasing temperature trend. However, in the classroom 1084, a 2 K setpoint increase to 23 °C is never accomplished. Moreover, on 17.11.23 and 01.12.23, classroom 1084 comes very close to the heating setpoint temperature while it is reduced by 1 K to 20 °C around 11 a.m. On 28.11.23, this setpoint temperature is reached at around the same time of day. While it is not fully known how many pupils were present in the room during these hours, the library’s smooth response to the room setpoint temperature signal and classroom 1084’s erratic response point towards the distinct influence of occupants on room air temperature in high-insulated buildings, like Ydalir school.

Concluding from the temperature trend, the library does not seem to have a high occupancy as the room temperature decreases gradually. The influence of internal gains from occupancy on the measured room temperature is more profound in classrooms like room 1084 where the fluctuation of room temperature between around 9 a.m. to 3p.m. is markedly larger. A detailed discussion of the classrooms’ behaviour is given in connection with Fig. 8.

Fig. 7 compares the same weekday for BAU operation and the load shifting operation to account for a similar occupancy pattern of the library room. Furthermore, two days with a similar average outdoor air temperature are chosen for the comparison to account for rather similar thermal conditions regarding heat losses through the building envelope or towards neighbouring zones (Fig. 7e).

For this case, two Mondays are compared where both days have an average outdoor air temperature of approximately −7 °C. Again, the measured room temperature follows the heating setpoint well, being 23 °C at 7 a.m. and being just below 21 °C at 12p.m. (Fig. 7a – right). The radiator supply temperature is rather constant throughout the whole day, whereas the return temperature drops significantly when room temperature setpoints are increased at 4 a.m. (Fig. 7b – right). The radiator valves are opened more to allow more flow through the radiator and thus more heat to be emitted to the room(s). The energy use (Fig. 7c) is shown as a 15 min average peak for the whole radiator circuit as room temperature setpoints are increased simultaneously in all rooms. Due to the simultaneous increase of the setpoints in all rooms a high energy peak occurs at 4 a.m. Ventilation is used to cool the room(s). The ventilation system is run at full capacity based on a schedule and can be adjusted to part-load depending on the CO_2 ppm-level or the measured temperature in the room (Fig. 7d). The system does not have a cooling setpoint, meaning that the ventilation runs at full capacity from 7 a.m. to 3p.m. unless the room temperature is below the temperature setpoint for heating. If the measured room temperature is below the heating setpoint, the ventilation flow rate is decreased to about 30 % of the normal flow rate.

It can be seen from Fig. 7d that the ventilation system is run at full capacity more often during the load shifting operation (“test”) because the room temperatures are above the temperature setpoint more often,

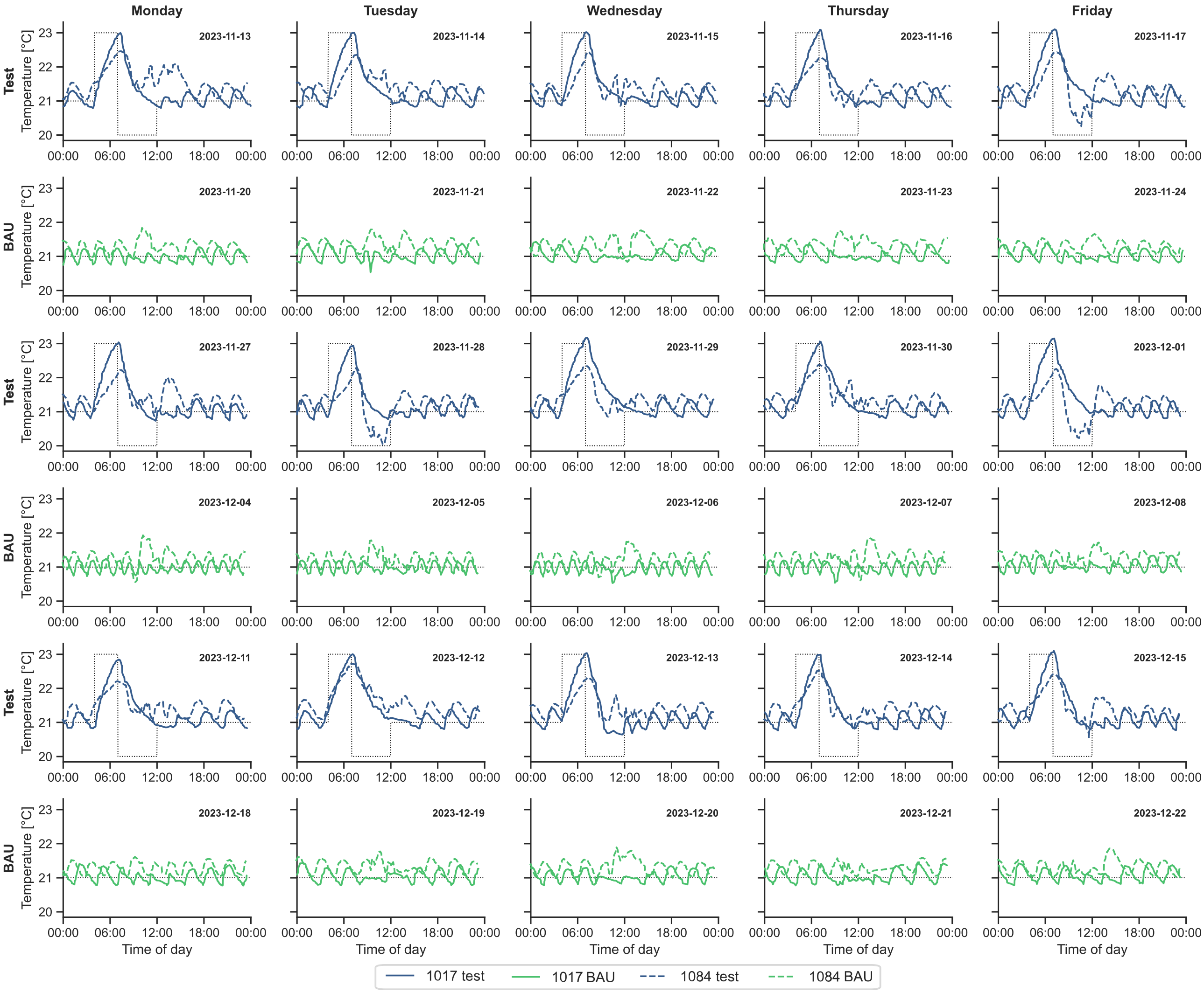


Fig. 6. Indoor air temperature for room 1017 (library, continuous lines), room 1084 (dashed lines) and indoor temperature setpoint (dotted black line) for all days in the test period organized by weekdays in the columns and alternating weekly pattern for test (blue lines)/BAU (green lines). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

particularly between 7 a.m. and 12p.m. after the rooms have been pre-heated. During BAU operation, the room temperature fluctuates around the setpoint of 21 °C. This leads to a more frequent temperature setpoint violation, and thus the ventilation flow rate is decreased more often in the BAU-case. The CO_2-levels are below 500 ppm throughout the entire experimental period and do not have any influence on the supply air flow rate in practice. Fig. 8 illustrates the thermal behaviour of four classrooms for the same days as used in Fig. 7.

In general, the rooms show a different behaviour considering the measured room temperature, ventilation supply flow rates, ventilation schedules and radiator valve openings. The energy use, radiator supply and return temperatures and outdoor air temperature are the same as in Fig. 6. The four rooms show a different thermal behaviour even though they all receive the same setpoint signal (Fig. 8a). The room temperature seems to be prone to internal heat gains from occupants since all four rooms have fluctuating room temperature even though there is very limited heating from the radiators (Fig. 8c) and a rather constant ventilation supply air flow (Fig. 8d). It can also be seen that the rooms do not manage to increase the room temperature to 23 °C within the three hours pre-heating period. This can have several reasons, e.g., under-dimensioned radiators in the respective rooms, too little heat available in the radiator circuit due to thermal heat losses in the heat distribution system or open doors. In contrast, radiator valves do not open fully even though the measured room temperature is below the setpoint. These issues have been communicated to the facility manager. Similarly to the library (room 1017, see Fig. 6), the ventilation air flow rates are decreased as soon as the room temperature is below the heating setpoint (rooms 1084 and 2076 in Fig. 8d). It can also be seen that air flow rates to the different rooms could be adjusted due to rather low measured air temperatures in the rooms.

Comparing the library (Fig. 7) to the classrooms (Fig. 8), the influence of internal heat gains from occupants on the room temperature is obvious. Heat gains from occupants contribute significantly to a slower temperature decrease in the classrooms even though the ventilation system runs at nominal air flow rate. Internal heat gains from solar radiation are assumed to have a minor effect on the room temperature compared to internal heat gains from occupants due to the low solar radiation in Norway during the experimental period (Fig. 3).

Room 1090 has a constantly high measured temperature of approximately 22.5 °C (Fig. 8a left) even though the setpoint is 21 °C in that room. It is not obvious from the measurement as to why such high temperatures are recorded for the room. The placement of the sensor cannot be the reason because the radiator valve is closed the whole night and the there is no ventilation either. This leaves room for speculation about an additional unknown heating source or that the sensor may not be calibrated properly.

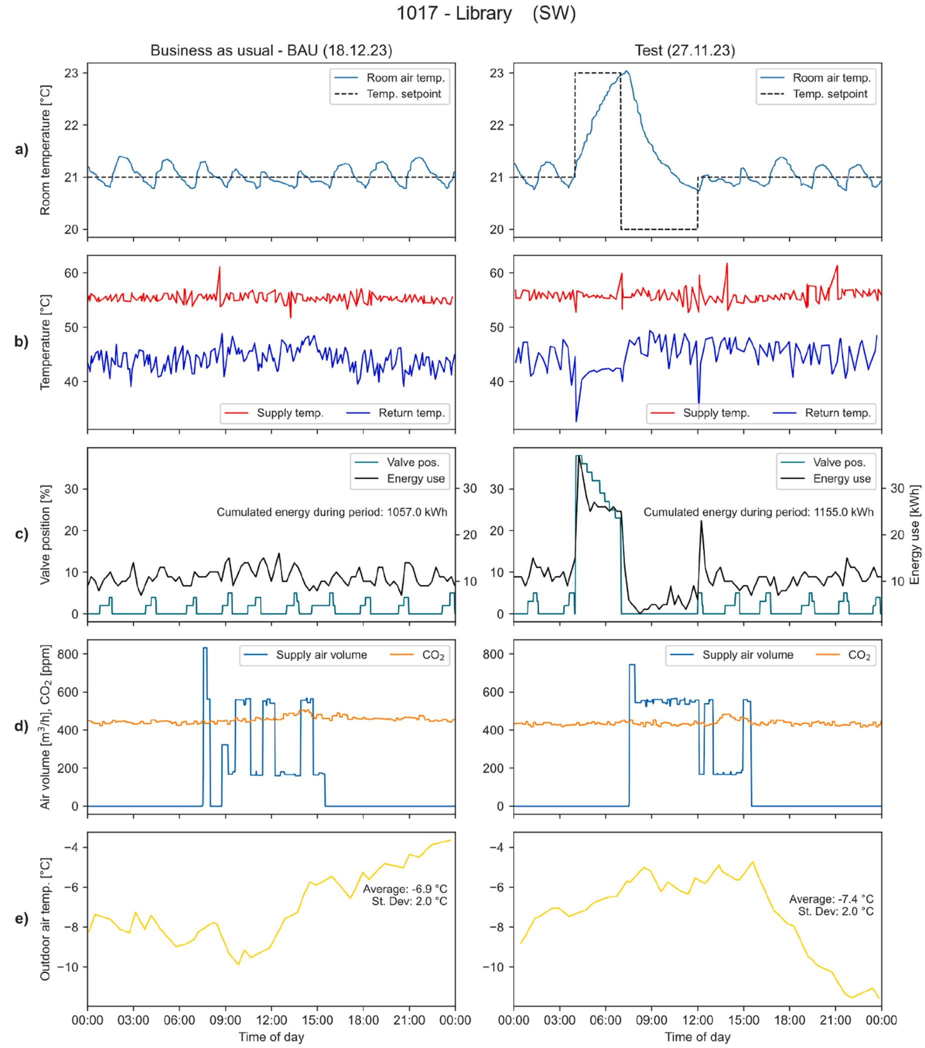


Fig. 7. Example for data collected for room 1017 (library) for a day with standard building operation (left) and a day with adjusted setpoints (right): a) room air temperature and indoor temperature setpoint; b) supply and return temperatures of the radiator circuit; c) valve opening position of radiator(s) in the respective room and energy use of the school's radiator circuit; d) ventilation supply air volume flow into the room and measured CO_2-level; and e) outdoor air temperature.

It is shown in both Fig. 7c and Fig. 8c that radiator valves are not opened between 7 a.m. and 12p.m., thus proofing that the load shifting operation manages to move heating loads to off-peak periods for the exemplary rooms. The load shifting is also proven by the quantitative evaluation of the KPI for the radiator circuit which are presented in Table 3.

Comparing the BAU- and load shifting scenario, the delivered energy is almost identical for both scenarios. Even though load shifting leads to higher energy use during the pre-peak periods up to 7 a.m., the energy use during the period from 7 a.m. to 12p.m. is reduced due to a lower room temperature setpoint. The difference in delivered energy $DE_{\text{test}} - DE_{\text{BAU}}$ is 83 kWh, corresponding to less than 1 %. The energy stress KPIs (ES and ES_{norm}) show an almost 50 % reduction in delivered energy during the pre-defined peak period for the test period compared to the BAU period, thus proving the load shifting capability of the schedule-based control. It is thus demonstrated that a simple controller can perform a significant load shifting without degrading the energy efficiency (while maintaining the same indoor temperature limits).

It is here pointed out that Fig. 7 and Fig. 8 only show a limited number of rooms whereas the thermal behaviour of the remaining rooms in the school building may differ from those exemplary rooms. Furthermore, the inertia of the technical components influences the energy use, for example, even though the room temperature setpoints are decreased at 7 a.m. sharp, the radiator valves do not close instantaneously, thus leading to heat being emitted from the radiators to the room in the periods just after 7 a.m. The peak load KPI (PL) shows that the maximum peak load is increased by almost 50 % from 78 kW (PL_{BAU}) to 117 kW (PL_{test}), because all room temperature setpoints are increased simultaneously, whereas for the BAU, the heating system is operated to simply keep a room temperature setpoint.

Looking at the normalized peak load PL_{norm}, the relative difference between the test and the BAU period is even larger. This is because the outdoor temperature at the time the hourly peak load during the BAU period occurred was -20.0 °C, while it was -12.3 °C during the test period. Consequently, normalization amplifies the difference between the two, highlighting its necessity when comparing measurement data for different external conditions.

In addition to the KPIs presented in Table 3, 17.8 % more air volume was circulated during the test period in which the load shifting scenario was implemented compared to the BAU period since the ventilation system runs with higher air flow rates for a longer period compared to the BAU. The extended periods with higher ventilation rates result in 2.5 % increased energy use for the heating coil of the ventilation system due to the preheating of the supply air in the rotary wheel heat exchanger during operation hours.

Fig. 9 shows the average hourly peak load per day. The error bars

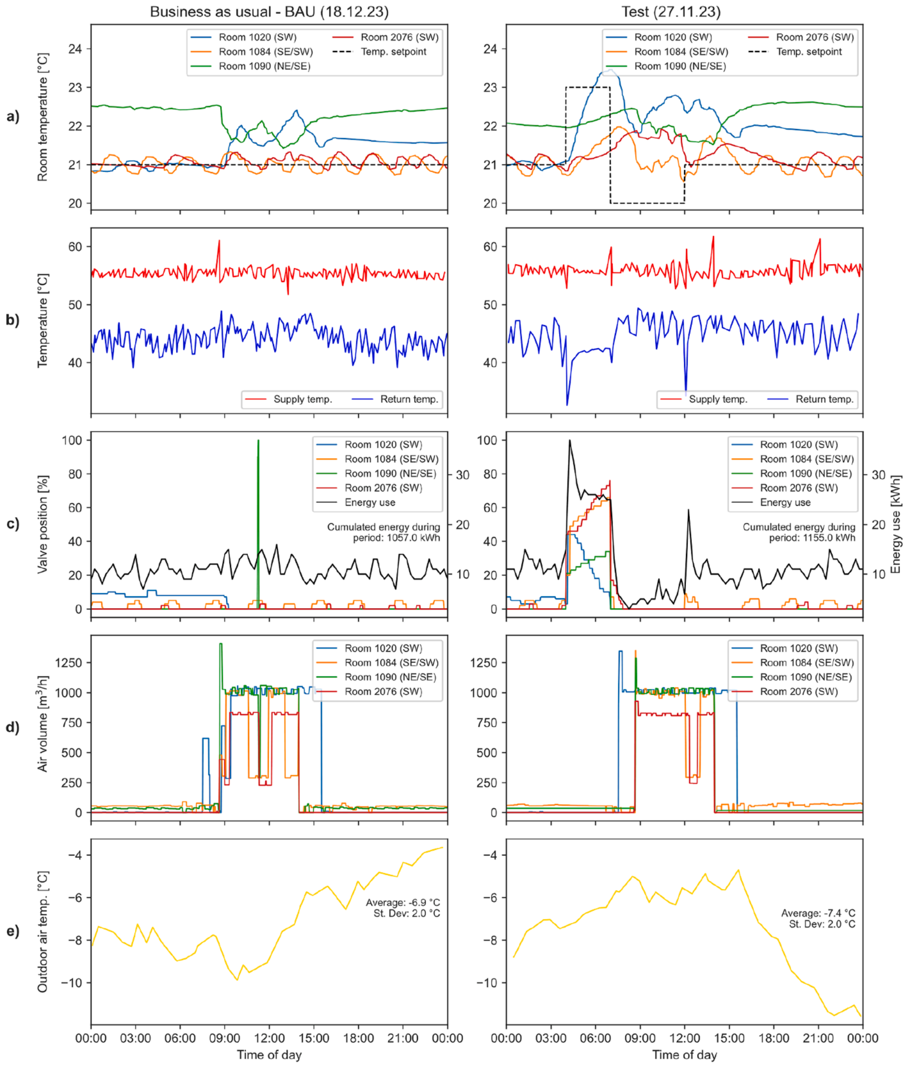


Fig. 8. Collected data for the classrooms 1020, 1084, 1090 and 2076 for a day with standard building operation (left) and a day with adjusted setpoints (right): a) room air temperature and indoor temperature setpoint; b) supply and return temperatures of the school's radiator circuit; c) valve opening position of radiator(s) in respective room and energy use of the school's radiator circuit; d) ventilation supply air volume flow into the room; and e) outdoor air temperature.

Table 3
Resulting KPIs.

#	KPI	KPI_{BAU}	KPI_{test}	Unit	Difference
1	DE	22,688	22,605	[kWh]	−0.4 %
2	DE_{norm}	45.9	45.6	[kWh/Kd]	−0.6 %
3	ES	3025	1591	[kWh]	−47.4 %
4	ES_{norm}	2.0	1.1	[kWh/Kh]	−46.7 %
5	PL	78	117	[kWh/h]	50.0 %
6	PL_{norm}	2.1	4.0	[kW/Kh]	89.2 %

indicate the range of highest hourly peaks of every day throughout the whole experimental period for the two respective scenarios. The coloured columns represent the respective arithmetic averages of all the values in the error bars.

3.2. Thermal comfort

The survey was carried out in 10 different rooms. In total, 212 thermal sensation votes (TSV) from nine classrooms and the library are collected during the experiment period. However, because room temperatures are decreasing relatively fast due to high ventilation rates, only votes before 09:00 each day are used for the analysis. This results in a total of 80 TSV, of which 38 and 42 are collected during test periods and BAU periods, respectively. The results (see Fig. 10) show that the pupils and teachers are in general quite satisfied with the indoor air temperature, as 63.4 % (test) and 63.2 % (BAU) of respondents feel "comfortable". Moreover, more respondents feel "too cold" rather than "too warm" which applies equally to the test (22.8 % "too cold" against 13.8 %) and the BAU (20.9 % "too cold" against 15.9 % "too warm") periods. On average, the room air temperature during the time of feedback is 21.9 °C and 21.2 °C for the test and BAU period, respectively. Furthermore, the average outdoor temperature during the two hours before the TSV is recorded for the load shifting and BAU periods being −4.9 °C and −6.2 °C, respectively.

Consequently, despite the small differences in room temperatures at the time of TSV recording and outdoor temperatures in the two hours preceding the time of TSV recording, the TSV for both periods are comparable. The TSV differences observed are not significant and indoor thermal comfort does not seem to be affected by the energy flexibility tests carried out in Ydalir school.

However, temperature changes over time can be experienced as uncomfortable. Table 4 shows the maximum temperature change among the selected rooms over time to ASHRAE 55–2017 [36]. The standard

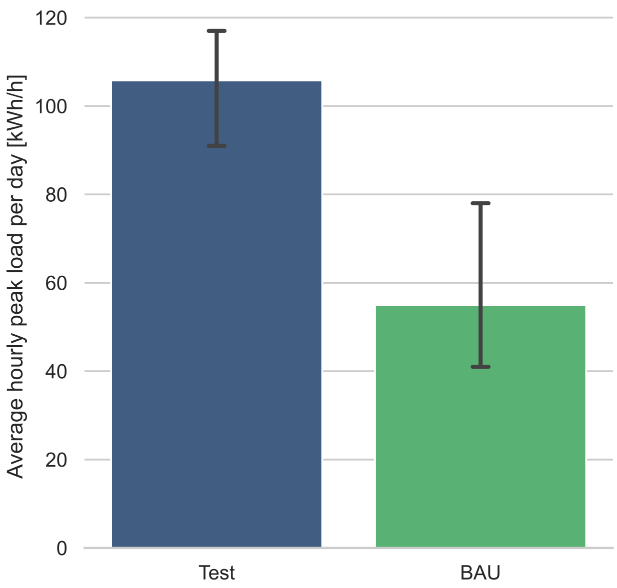


Fig. 9. Average hourly peak load per day during the test period (blue) and the BAU period (green) with bars indicating the minimum and maximum value during the respective periods. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

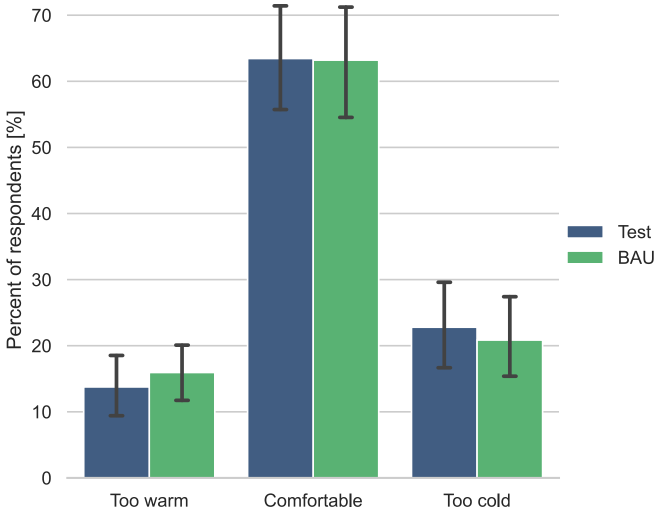


Fig. 10. Average thermal sensation vote for the test period (blue, n = 38) and the BAU period (green, n = 42) with bars indicating the 95 % confidence interval. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 4
Maximum temperature change of the selected rooms during the BAU and test period, compared to ASHRAE 55–2017 for different time periods.

Time period [h]	Maximum temperature change [K] ASHRAE 55–2017 [36]	BAU	Test
0.25	1.1	1.1	0.9
0.5	1.7	1.6	1.2
1	2.2	1.8	1.6
2	2.8	1.9	2.4
4	3.3	2.5	2.7

classifies temperature variations as either temperature drifts and ramps or temperature cycles. It provides limits to a maximum operative temperature variation over different time periods. Drift and ramps are defined as “monotonic, non-cyclic changes in operative temperature” which is corresponding to the temperature decay phase of the presented experiments. Since the BMS does not record operative temperature in the school, the room air temperature was used instead for Table 4. The maximum change in room air temperature over a distinct time period is within the limits suggested by ASHRAE 55–2017. Changes are larger for the BAU period compared to the test period for time periods up to 1 h, whereas the temperature changes over 2 h and 4 h are larger for the “test” period. These results show that the room air temperature setpoint changes applied during the “tests” lead to acceptable variations of room air temperature over time compared to normal building operation with constant setpoints. This suggests that it is unlikely that adverse consequences in terms of user acceptability should be expected from the tests presented in this study. It is worth noting that the temperature change is strongly related to the building construction (meaning its time constants). In the presented experiments, the building is highly-insulated which limits the temperature decrease when not heated actively. Therefore, the conclusions regarding the temperature decay and thermal comfort cannot directly be extended to all buildings, especially with a building envelope with a lower thermal performance.

3.3. *Practical challenges in the study*

Due to the applied nature of this study, there are some practical limitations and challenges for integrating control strategies that deploy the BEF and for analysing their effect on the thermal behaviour of the building. All challenges were experienced during this case study and are outlined in Table 5.

4. Conclusions

Demand side flexibility of buildings can play a major role in the ongoing energy transition. Recent studies ([14,16,18]) point out that less invasive control strategies, meaning control approaches that are less data-dependent than component level MPC-strategies, are necessary to speed up the widespread implementation of energy flexibility approaches in practice. This paper demonstrates the load shifting potential in a real school building in Norway by deploying the inherent space-heating flexibility of the building. With this, the study contributes to bridging the gap between theoretical research and practical solutions for energy-flexible building operation from two angles: i) a technical as well as ii) from a thermal comfort point-of-view.

The *first research question* focuses on how simplified control approaches can leverage building energy flexibility to enhance load shifting in educational buildings. A schedule-based control strategy to adjust room temperature setpoints is implemented in a school building that has a water-borne heat distribution system and is connected to a district heating grid. The control strategy aims at pre-heating the rooms in the school by shifting heating loads to pre-defined off-peak hours, 4 a.m. to 7 a.m. It is shown that the schedule-based control is very efficient in shifting loads to off-peak periods, thus proving to be a simple measure to deploy the building energy flexibility without compromising energy efficiency. However, to avoid high peaks resulting from a simultaneous increase in room temperature setpoints, a more segmented setpoint increase in a coordinated manner is recommended. Regarding pre-heating of rooms as a means of deploying the building energy flexibility, variations in thermal dynamics of similar rooms and the influence of ventilation on the measured room air temperature show the need for controlling the heating and ventilation system in a combined manner because too much or too early start-up of the ventilation will diminish or even eliminate the benefits of pre-heating the rooms. Additionally, the study highlights the substantial impact of internal heat gains on room temperature trends and confirms that pre-heating rooms, along with internal heat gains from occupants, can prolong the requirement for active heating throughout the day in the case study building. Those aspects could be considered more explicitly with more advanced control frameworks. However, it is pointed out that the school building is well-insulated and is thus a relatively good heat storage compared to older less-insulated buildings. For well-insulated buildings the energy efficiency is less sensitive to the time when the increase in set-point temperature is applied. In future work, the same experiment could be repeated in an older building to investigate whether energy flexibility and efficiency can still be reached simultaneously.

Table 5
Challenges, effect of the challenges on control integration as well as data analysis and recommendation to tackle the challenges based on this case study.

#	Challenge	Effect on control integration or data analysis	Recommendation to tackle the challenge
1	Incomplete or outdated functional description of the technical systems	Uncertainty about how the technical systems are operated; More cumbersome analysis since a first analysis is required to clarify how the building works, and then the load shifting potential can be analysed.	Ongoing communication and knowledge transfer between system integrator and technical personnel of the building; Prioritization of continuous data analysis by building operator.
2	No possibility for automated setpoint changes in the BMS	The building manager has to apply setpoint changes ad-hoc making it inconvenient to apply pre-heating in the middle of the night.	A “schedule function” as a minimum requirement in the BMS to adjust temperature setpoints in a less cumbersome manner. BMS provider should programme this option into the BMS interface.
3	Rooms have different thermal behaviour	Desired room temperature not reached at a specific point in time, e.g., 7 a.m.	Schedules for temperature setpoints should be tailored for each room for each specific case (optimal start of heating).
4	Influence of ventilation on measured room air temperature	As ventilation usually provides cooling, the settings for the ventilation system (cooling setpoint and ventilation flow rates) impact how fast a room temperature decreases (without internal heat gains). Room temperature evolution would be different, if the ventilation system had different operation settings.	Regarding shifting the heating demand, settings for the ventilation system and heating system should be seen in combination, as the effect of pre-heating diminishes with too early start-up of the ventilation or too much ventilation.
5	Availability of data and documentation	Cumbersome process to gather all relevant information especially for analysing and understanding the measurement data.	Building operator should have a central repository with complete documentation related to the building.
6	Availability of occupancy schedules for each room	Occupancy influences the amount of internal heat gains in a room and thus room temperature evolution.	Information on the room occupancy schedules in classrooms helps to develop improved ventilation and heating schedules aiming to maximize the benefits of deploying the BEF. Occupancy sensors can be placed.
7	Bias in the survey responses due to activity level of pupils	Pupils walking or biking to the school in the morning will have a higher metabolic rate upon arrival at the classroom and may perceive the indoor environment as too warm	Close collaboration and continuous communication with the school employees to determine the best possible time for answering the survey during a hectic school day. The beginning of the first lesson is closest to the pre-heating event, but pupils may have higher metabolic rate. A solution can be to collect more information (metadata) from the pupils during the survey.

The second research question aims to evaluate how building occupants perceive changes in indoor climate and building operation when deploying the BEF with simplified controls. To that end, a simple survey is used to document the perceived thermal comfort in ten exemplary rooms, where the pupils are asked to rate their thermal comfort level. No significant differences in the thermal sensation vote by the pupils is recorded for both periods, the BAU scenario and when the schedule-based control is active.

The third research question investigates which practical challenges exist in integrating simplified control approaches, designed to deploy building energy flexibility, into existing buildings and BMS. Several practical challenges related to the implementation and evaluation of a simplified load shifting control are experienced. One significant challenge is the presence of incomplete or outdated functional descriptions of technical systems, leading to uncertainty about system operation and impeding the load shifting potential as well as its analysis. Additionally, the absence of automated setpoint changes in BMSs poses challenges for building managers, making it inconvenient to implement energy flexibility measures such as pre-heating. Thus, energy flexible building operation should ideally be considered during the tendering phase of a building project, so that the BMS can fulfil the technical requirements that need to be in place for it once the building operation starts. It is also strongly recommended to have a walkthrough in the school to complement the measurement data and to gain a better understanding of the data.

Future research should focus on room specific thermal behaviour analysis to better understand and maybe even predict temperature variations within buildings to tailor temperature setpoint schedules for each room more accurately. Furthermore, the operation of ventilation and heating systems should be considered in an integrated manner focusing on coordinated control algorithms that take into account both, the effect of pre-heating rooms as well as space cooling through room ventilation.

CRediT authorship contribution statement

John Clauß: Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Methodology, Investigation, Data curation, Conceptualization. **Johannes Brozovsky:** Writing – review & editing, Visualization, Software, Investigation, Formal analysis, Data curation, Conceptualization. **Laurent Georges:** Writing – review & editing, Resources, Project administration, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The authors do not have permission to share data.

Acknowledgements

This paper has been written within the Research Centre on Zero Emission Neighbourhoods in Smart Cities (FME ZEN) under grant number 257660. The authors gratefully acknowledge the support from the ZEN partners and the Research Council of Norway. In particular, the authors would like to thank Terje Smedbakken and Monica Bekkelien from Ydalir school for their support during the tests and Elverum municipality for granting access to the school. Furthermore, the authors would like to acknowledge IEA EBC Annex 81 “Data-driven smart buildings”.

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