Data driven energy efficiency in an air heated office building in Norway

Natasa Nord[a], *Ingrid* Jæger Landsnes[b], *Yuemin* Ding[c]

[a] Department of Energy and Process Engineering, Faculty of Engineering, Norwegian University of Science and Technology, Trondheim, Norway, natasa.nord@ntnu.no.

[b] Enterprise ventilation, Gunnar Karlsen, Trondheim, Trondheim, ingrid_landsnes@msn.com.

[c] Department of Electrical and Electronic Engineering, Tecnun School of Engineering, University of Navarra, San Sebastián, Gipuzkoa, Spain, yueminding@ceit.es.

Abstract. There are lots of data stored about buildings that could be better used to improve the operation of existing and new buildings. In the long run, this means that building data can be used much more efficiently for energy, heat rate, and electricity reduction based on price and load. However, building data are only stored and the knowledge that may be found in this data is not fully utilized. The aim of the study was to evaluate potentials and opportunities with continuous energy, heat rate, and power reduction in an all-air heated office building in Trondheim, Norway. The observed building has an area of 14 000 m² and the building was built according to the passive house standard. The background for the work was that high peak loads in electricity and heat are challenging for both the district heating and power grid. By reducing or moving the energy use of the ventilation heat to periods with low grid loads, cost savings can be achieved through a reduced rate in district heating and electricity. In this study, a model of the building was created in the simulation program IDA-ICE, where data about building body, outdoor climate, energy supply, energy distribution, set points for room control, operation and schedules were used from a real building. This included measurements of the outdoor temperature, supply temperature, internal loads, electricity use, district heating, and hot water, as well as indoor temperatures and air flow rates. Various scenarios were developed to reduce peak loads in heating and electricity with the focus on controlling the ventilation system. The results for the annual simulation showed a reduction in ventilation heat rate from 12% to 33%. Further, the results showed a cost saving for heat and electricity from of 10% to 16%. The study may be useful for facility managers, operators, and end users of office buildings that want cost-effective building performance improvement.

Keywords. Peak load, ventilation, BEMS, building simulations, demand response.
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1. Introduction

Energy efficiency measures in buildings imply reduction of demand load and energy requirements in buildings, without sacrificing indoor thermal comfort. These measures may range from good building insulations, efficient building service systems, effective operation and maintenance, and expert-based utilization of building energy monitoring [1]. An example of energy efficiency measures is implementation of improved control strategies on a single building service system or on different systems such as heating, ventilation, and domestic hot water use. The work flow for identification of potentials for energy efficiency measures may be defined by following steps: 1) identify real energy use in buildings [2] by performing energy auditing; 2) suggest and introduce energy efficiency measures; 3) perform measurement and verification of the introduced measures; 4) perform economic analysis. Depending on the performed study, evaluation of the energy efficiency measure impacts may be theoretical or real. In this study, potentials and opportunities with continuous energy, heat rate, and power reduction in an all-air heated office building in Trondheim, Norway, were evaluated by utilizing the building energy and management system (BEMS) data and a building simulation tool. An economic analysis was also performed to estimate the economic benefits of the suggested measures.

Modern buildings have usually a well instrumented energy and indoor environment monitoring system

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such as BEMS. Due to development of the communication technologies, these systems are getting improved. However, their full potential to operate buildings efficiently and to work together with the energy system is not yet well developed. These systems may produce lots of monitoring data, but their full potential to develop real building knowledge for continual building energy efficiency improvement is not yet achieved. In a review paper where 30,000 full-text building-related articles have been extracted for text mining, it was found that data science techniques are applied more for operation phase applications such as fault detection and diagnosis (FDD), while being under-explored in design and commissioning phases [3]. Specifically, when it comes to use of building data to development of control strategies in buildings, the application is on an average level. A survey study on data-driven predictive control strategies for energy efficiency in buildings led to 10 insights considering improvement of building energy performance. Among else two insights are very interesting: 1) minority of studies addresses the aspect of BEMS integration and 2) systemic interdependencies or conflicting control commands are rarely studied [4]. An approach for data-driven building energy modelling with feature selection and active learning for data predictive control was proposed in [5], where a detail workflow for calibration of the building simulation model was proposed. Based on the above mentioned, there is a huge need to make better utilization of the BEMS data to develop building knowledge for continual building energy efficiency improvement Therefore, in our study, methods to actively utilized BEMS data for building simulation model calibration and control improvements for energy efficiency were suggested. Further, a systematic approach to avoid conflicting control outputs was suggested. The last was possible, because the observed case building is an all-air heated building [6].

A data-driven methodology for enhanced measurement and verification of energy efficiency savings in commercial buildings where an innovative technique to evaluate the building's weather dependency to design a model able to provide accurate dynamic estimations of the achieved energy savings and the building energy simulation software EnergyPlus, as well as monitoring data from real-world buildings was suggested in [7]. This study is an excellent example how to combine real measurements, building simulation tools, and data mining techniques for measurement and verification of energy efficiency savings in buildings. To evaluate the building's weather dependency, energy signature curves were firstly developed and analyzed in [7]. Similarly, in our study, real measurements and a building simulation tool were combined, while to develop simple yet effective energy savings measures, energy signature curves were firstly analyzed.

Demand response will play an important role in the smart buildings and energy systems of the future. Today, there are many studies that have gone into depth on Demand Response for the power grid, but a similar progress has not yet been made for the district heating systems and building service systems [8, 9]. Demand controlled ventilation with temperature dependent flow rate control [10] implemented in an all-air heated building gives a huge potential to implement demand response in a reliable way in buildings for energy efficiency and decreasing of the demand load. Optimization and implementation of cost-effective energy efficiency measures in an all-air heated building in Norway has been presented in detail in [11, 12]. However, thorough analyses on both decreasing heat and electricity demand load in buildings through data-driven control strategies is still missing. Therefore, in this study different data-driven strategies were developed to intensify energy efficiency and decrease the demand load for heating and electricity.

The aim of the paper was to use the building simulation tool combined with the BEMS data to identify potentials for demand load reduction in an all-air heated office building. Reduction of peaks for ventilation heating, would affect fan power, indoor climate, and could lead to cost savings for heating and electricity. In this study, an office building located in Trondheim, Norway, was analyzed. The building is all-air heated. This allowed possibility to utilize the ventilation parameters for the peak load reduction in both heating and electricity use. Temperature measurements, schedules for internal loads, and district heating use were used to calibrate the model. Further, consequent simulation-based analyses were developed for various scenarios to identify potential for load reduction. The aim of this analysis was to estimate whether the building might have the potential for reduction of peak loads through data-driven control strategies.

Innovations in the study are extensive utilization of the BEMS data and simulation results to identify improvement scenarios for energy efficiency and the peak load reduction. For example, a thorough analysis of the energy signature curves showed the time delay between the supply air temperature in ventilation and the highest demand.

The rest of the paper is organized as the following. Method consisting of the model presentation, calibration, and scenarios is presented. Results are given by firstly showing daily analysis and then annual results.

2. Methods

In this section, methods used in the study are presented. To perform this study, combination of building simulation and real building data were used. BEMS data were used for two purposes: 1) to calibrate the simulation model and 2) to suggest new control strategies in ventilation. Finally, the improvement scenarios to decrease the peak loads were suggested based on a combination between the BEMS data and consequently produced, organized, and analyzed building simulation results.

Based on the building data, the building model was developed using the dynamic simulation tool IDA ICE 4.8 [13].

Since most of the BEMS data were collected for 2019, the boundary conditions considering indoor and outdoor temperature were the respective data for 2019. Considering the economic analysis, the current energy price models in Norway were used.s

2.1 Model calibration

To calibrate the model, monitoring data on internal loads, occupancy presence, and supply air temperature were used. In this study, data from 2019 were available.

To calibrate the building simulation model, the simulated space heating (SH) demand was compared with the real building SH demand. The domestic hot water (DHW) use was used as an input because it was separately measured. Consequently, it was enough to compare the simulated and the measured SH demand to calibrate the model. Comparison of the hourly values was performed to calibrate the model properly. This means that it was assumed that the simulated duration curve for the SH corresponds to the measured duration curve for SH. It was assumed that there was enough available heat, so that the set point for the supply air temperature in ventilation was reached in the simulations.

Considering the indoor environment in the model calibration process, it was observed that the CO_2 level in the simulations were below the maximum setpoint for the CO_2 level. This meant that it was reasonable to allow modulation on the air volume rates that were controlled according to the indoor temperature and the CO_2 level in the further scenarios without negative consequences on indoor environment.

2.2 Case building and building model

An office building located in Trondheim, Norway, was investigated in this study. The building area is 14 000 m^2. Some details about this building are introduced as follows. The appearance of this building is shown in **Fig. 1**. The building is composed of six floors. There are two floors underground, the lower one is completely used for paring area, while the higher one is used for cafeteria, office room, meeting rooms, and partially for the parking area. The other four floors above the ground are composed of a mixture of meeting rooms, single-celled offices, miscellaneous rooms, and open-landscape working areas. The heat demand of this building is caused by SH and DHW. The heating supply is provided by district heating. The ventilation system in this building is a variable air volume (VAV) system. The heating system in this building is an all-air heating system [6]. This means that all space heating is delivered by ventilation.

Fig. 1 - Observed office building.

The thermal parameters of the observed building are summarized in **Tab 1**. The building was designed according to the Norwegian building code TEK17 [14]. The building code TEK17 is similar to the passive house standard.

Tab. 1-Parameters of building envelope.

	U-value (W/m^{2}K)
Outer wall	0.18
Inner wall	0.15
Ground floor	0.13
Roof	0.13
Windows	0.8
Doors/openings	1.2

BEMS consists of two systems: 1) the indoor environment monitoring and 2) energy monitoring system. These two systems were used to retrieve building operation data. There are many sensors installed in this building to sample parameters including occupancy state, indoor and outdoor air temperature, energy use, etc.

The building model in IDA-ICE is shown in **Fig. 2**. In total the building was modeled with 425 zones. All the zones are grouped as internal offices, external offices, meeting rooms, toilets, cafeteria, and the parking areas.

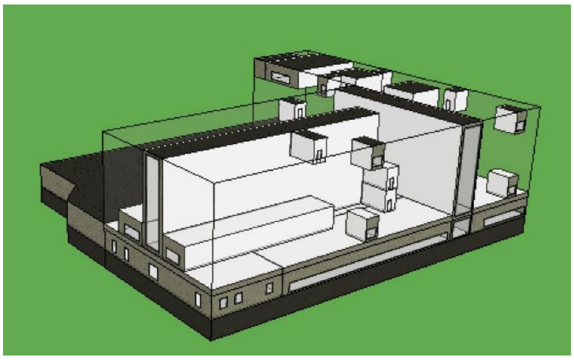

Fig. 2 – Building model in IDA-ICE.

The internal loads used as the simulation input are given in **Fig. 3**. These profiles were obtained by statistical analysis of the monitoring data from the indoor environment monitoring system.

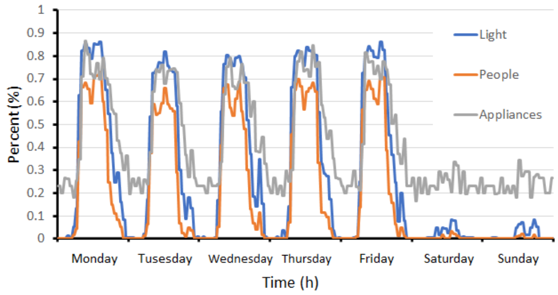

Fig. 3 – Weekly profile for internal loads

2.3 Scenarios for decreasing peak loads

Scenarios for decreasing the building loads focused primary on decreasing of the heat load, while decrease of the electricity load was a by-product. Decrease of the heat loads would also influence the electricity loads, because the building is all-air heated. Four scenarios were defined to decrease the peak loads. The scenarios are based on control of the supply air temperature and air amount in the ventilation system.

To formulate the scenarios for decreasing the heat load, detail analyses of the measured and simulated data were performed. **Fig. 4** shows a summary and influence of the supply air temperature and the ventilation heat rate. The results in **Fig. 4** were obtained based on simulation. The supply temperature was successively moved for each hour and a new simulation was generated. Based on all these results, **Fig. 4** was organized.

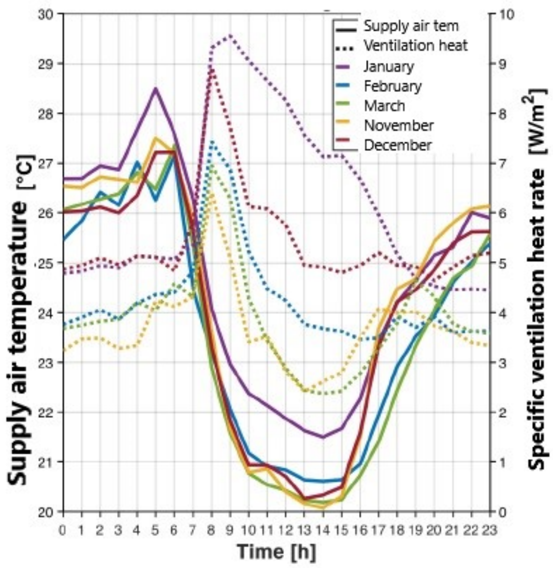

Fig. 4 – Daily average months of the supply air temperature and ventilation heat rate in heating months

The analyses included thorough analyses of energy signature curves on hourly level. Ventilation heat demand was compared to the outdoor temperature and the supply air temperature for different months and working and non-working hours. The analysis showed a clear dependency of the ventilation heat demand on the outdoor temperature in the heating period from November to March. In addition, a linear relationship between the ventilation heat rate and the temperature difference between the supply ventilation air and the outdoor temperature was noted. All these gave the motivation to introduce different control scenarios on the supply air temperature to decrease the heating peak loads.

Fig. 4 shows a clear time delay in the peaks between the highest supply air temperature and ventilation heat for working days. Therefore, this delay was studied further and utilized to develop the peak load decreasing scenarios. The time delay between the highest supply air temperature and the highest ventilation heat rate was from 4 hours in January to 2 hours in December, March, and February. In general, the higher temperature delay was noted in colder months.

Based on the analysis of the time delay between the highest supply temperature and the aim to decrease the heat demand load to estimate the potential for the demand response, the following four scenarios were tested as shown in **Tab. 1**.

Tab. 1 – Scenarios for decreasing heat load

Scenario	Description
Scenario 1	Moved the highest supply temperature until the lowest peak was achieved
Scenario 2	Supply air temperature was increased or decreased for the coldest or warmest days in periods for 1 – 2 K
Scenario 3	Set point for the supply air temperature was set between 21 - 24°C
Scenario 4	The set point for the air flow rate for the VAV system was to 0.7 to 3 L/s/m²

The first two scenarios in **Tab. 1** were suggested by detail analyses of the time delays between the highest peak load and the highest supply air temperature. The idea behind Scenario 1 was developed by a successive moving of the supply ventilation air temperatures given in **Fig. 4** for one hour and analyzing the achieved peaks. For each moved supply temperature profile, the heat loads were produced by the simulation and compared. It was observed that if the supply air temperature with the highest value at 5 AM as shown in **Fig. 4** was moved to 4 PM, the lowest heat peak load was achieved. The indoor temperature was also followed all the time and satisfactory values were also obtained. Scenario 2 was reached in a similar way as Scenario 1, except that it was noted that it would be worth just to increase or decrease the supply air temperature for 1 – 2 K in the case when the outdoor temperature was lower or higher, respectively. In general, in the heating period, the supply temperature was increased by 1 – 2 K. Scenario 3 was reached by allowing a wider range for the indoor air temperature to variate. Finally, Scenario 4 was suggested by decreasing the limit for the maximum air flow rate.

2.3 Energy cost models

To calculate the impact of the suggested scenarios for peak load decreasing, energy cost for the observed building were calculated. The energy costs were calculated both for heating and electricity based on the current pricing models in Norway.

Electricity cost was calculated as:

$$C_{el} = C_{gf} + C_{ee} =$$

$$(C_{fix} + C_{gen} + C_{gp})_{fg} + (C_{en} + C_{add})_{en} \qquad (1)$$

In Equation (1) there are two main items to be considered, grid fee, C_{gf}, and energy cost, C_{gf}. The grid fee part consists of three parts, fixed part, C_{fix}, that is the same for all the costumers in the same group, energy part, C_{gen}, calculated based on the energy use, and the grid fee part due to power extraction, C_{gp}, calculated based on the maximum power taken during a month.

Heating cost was calculated in the same way as the electricity cost in Equation (1), except that there is no fixed part, C_{fix}, in the calculation of the heat cost.

The specific values used to calculate the heat and electricity cost are given in **Tab. 2**. The cost data in **Tab. 2** are given in Norwegian Kroner (NOK) and the current valuta ration is about 10 NOK = 1 EUR.

Tab. 2 – Energy cost data

Type of cost	Price	Electricity	District heating
Grid fee	Fixed (NOK/year)	8800	
	Energy (NOK/kWh)	0.05	0.05
	Consumption tax (NOK/kWh)	0.158	0.158
	Power rate (NOK/kW/month)	40 - 60	40 - 60
Energy	Energy (NOK/kWh)	NordPool hourly marked	0.3– 0.5
	Addition (NOK/kWh)	0.03	0.03

The presented results and influence of the peak load decrease on the cost saving are very dependent on the energy pricing models. However, for the purpose of this study, only the current model and the values given in **Tab. 2** were used.

3. Results

In this section, firstly the results on the model calibration are given. Further, a simple example how change in the supply ventilation air temperature influenced the heating demand for one cold day is given. Finally, annual analysis for the heating load and cost is given.

3.1 Calibrated model

To calibrate the model, the input values on the occupancy, internal loads, and ventilation control were used. To recall, DHW use was used as an input, because it was separately measured. Therefore, to check the model quality, the SH demand was checked, and the results are given in **Fig. 5**.

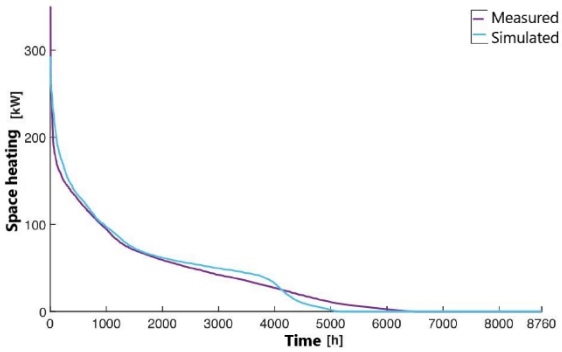

Fig. 5 – Model calibration

The results in **Fig. 5** showed that the SH total heat demand of the calibrated model was 3.4 % higher and the maximum peak demand was lower for 16.3 %. Based on the other parameters and the result analysis, the model was considered reliable for further use.

3.2 Daily energy use analysis

To illustrate importance of decreasing the total energy demand and importance of the supply air temperature in ventilation, the results in **Fig. 6** are shown. The results are given for one cold day when the outdoor temperature was – 10.5°C. The results are given for the calibrated model and three different control strategies.

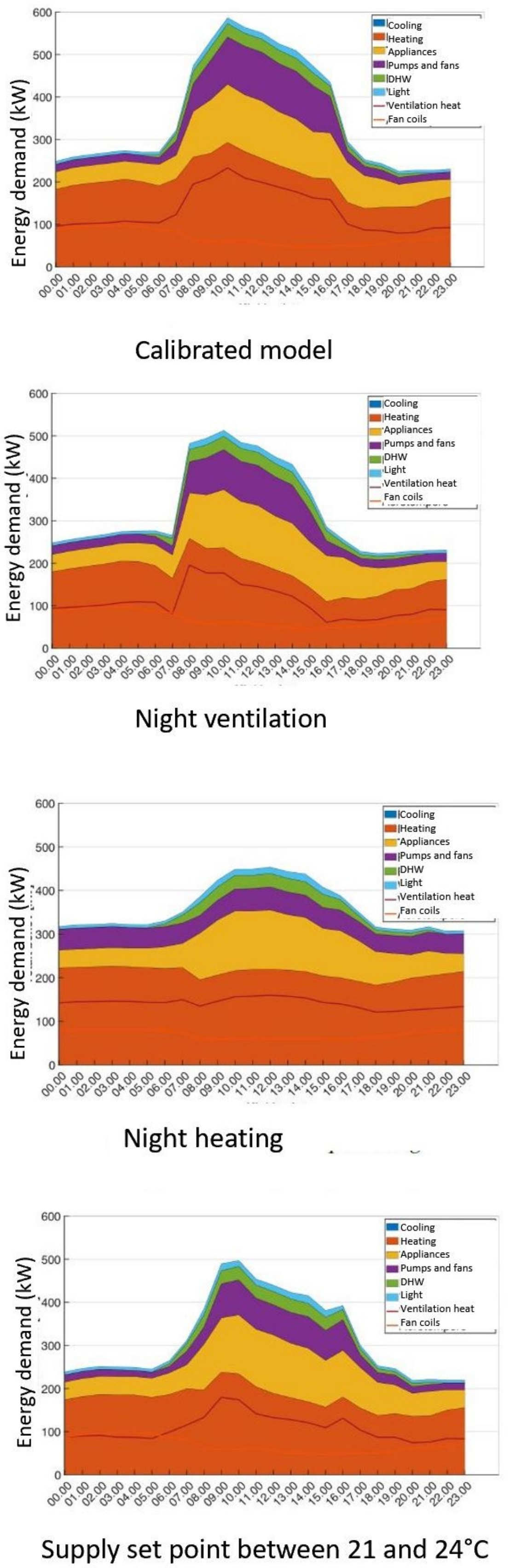

Fig. 6 – Daily analysis of the heat load reduction due to different ventilation control

From **Fig. 6**, it is possible to identify how small changes in control might reduce the peak heating demand up to 23%. To identify this decrease in **Fig. 6**, consider the horizontal line at 500 kW heating demand. For the Calibrated model, the highest peak was above that value, while for the other scenarios the highest heating demand was lower. It is very interesting to notice that the control strategy Night heating when the office was heated up to certain level gave the lowest variation in the heating demand. Electricity use for fans and pumps was decreased by 26%, when comparing the calibrated model and the model when the indoor temperature variated from 21 - 24°C. To follow the decrease in the electricity use for fans and pumps, follow the pink area in **Fig. 6**. Based on the results in **Fig. 6**, it is obvious that the different control in ventilation reshaped much electricity demand for fans and pumps. In the control strategy with the night heating, the electricity demand for fans and pumps seems to be constant over the day. This result is very good, meaning that only electric appliances and DHW, or occupancy related energy use, were changing the building demand.

4.2 Annual energy use analysis

To present results on annual energy use, firstly duration curves for the scenarios given in **Tab. 1** are given in **Fig. 7**.

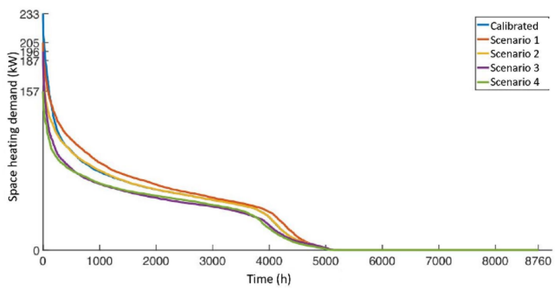

Fig. 7 – Duration curves for different control scenarios

In **Fig. 7**, it is possible to notice decrease in the peak load for SH and in the total SH demand due to the implemented control strategies. As a summary, the peak load was mostly decreased when the range for the maximum air flow rate was decreased, Scenario 4. In that case, the peak load was decreased for 33 %. The total heat use was mostly decreased when the temperature range and the air flow rate range were changed. The decrease in SH was about 17%.

Finally, the total annual cost for electricity and heat are given in **Fig. 8** for the different scenarios introduced in **Tab. 1**. As a summary, the cost results in **Fig. 8** show that the highest cost reduction were achieved in Scenarios 3 and 4. The results for Scenario 4 are not given directly in **Fig. 8**, because they are similar as for Scenario 3. In Scenario 1, even an increase in the heating cost was achieved, because the resulting cost effect of the decreased peak load was lower than a small increase in heating energy demand.

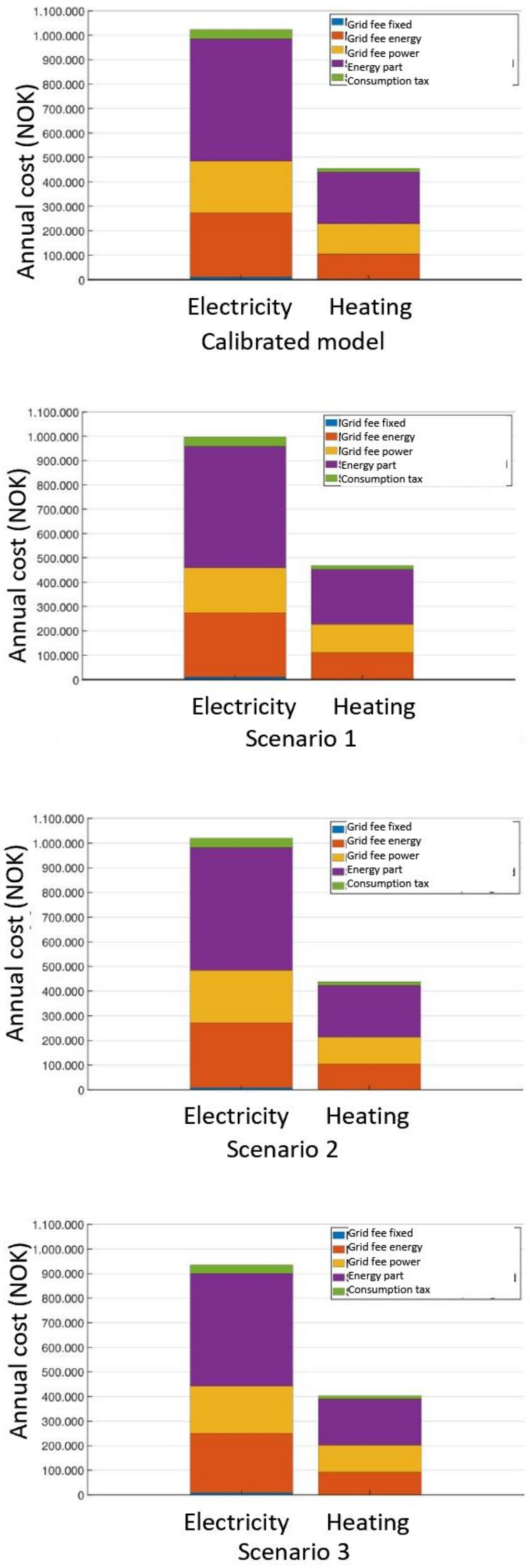

Fig. 8 – Annual cost for different control strategies

The best cost savings achieved in Scenario 3 and 4 are due to decrease in the peak loads and energy use. These decreases were achieved due to limited possibility for modulation of the air flow rates. By analyzing the results in **Fig. 8**, it is possible to notice that modulation of the air flow rates may be used as a demand response measure to decrease the energy cost. Scenario 1 that was suggested based on the data analysis and is simple to implement, just by moving the highest temperature might give some saving results specifically on the peak demand, while the final economic results depended highly on the energy pricing model and weighing between energy and heat rate in the pricing model. In general, all the results in **Fig. 8** showed potentials and opportunities with continuous energy, heat rate, and power reduction in an all-air heated office building. Thereby, it may be concluded that all the suggested scenarios may be considered as possible demand response measures. However, the final economic benefits are dependent on valid pricing models. The results in **Fig. 8** are valid for the energy price models and values given in **Tab. 2**. Therefore, a further analysis on the price models may show different results.

4. Conclusions

In this study, various scenarios were studied to reduce peak demand for the ventilation heat in an office building with all-air heating. The simulation program IDA-ICE was used to perform the analysis. Different scenarios were simulated for a specific cold day and for the whole year to analyze how demand reduction might affect the ventilation heat, fan power, indoor climate, and costs for thermal and electrical energy. Detailed monitoring data including indoor environment, ventilation parameters, and energy use were used to calibrate the model and to develop the scenarios.

To develop control scenarios for decreasing peak load, detail analysis of the simulation results was performed. The idea of the analysis was to identify time delay between the highest supply temperature and the highest peak load for heating. This approach may be useful for practical applications when supply temperature may be moved to decrease the peak load.

The results show that the different scenarios give different changes in the peak load both when it comes to heating and electricity. The best results were achieved then the temperature range for the allowed indoor air temperature was bigger and when the range for the maximum air amount was lower.

Future research should include the following. Influence of different energy pricing models that would motivate higher peak load reduction. In this work, the focus was solely on the heat load decrease. However, further study on different control strategies in ventilation such as the return air compensation control may be be tested.

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