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Validation of a Simplified Model Predictive Control of a Low Exergy Embedded Heating and Cooling System

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ABSTRACT

Powerhouse Telemark is a low carbon plus energy project in Porsgrunn, Norway. The building is currently in a commissioning phase, but with most of the building under normal operation. The heating and cooling of the building is primarily done by a low temperature radiant floor heating system which is reversed in summer and used for high temperature cooling. The low temperature heating is provided by a geothermal heat pump and the high temperature cooling is provided by free cooling from the energy wells. The flooring system uses embedded pex-pipes in a 100 mm concrete slab with a polished surface to keep a minimal thermal resistance between the hydronic system and the room interior. This gives the possibility of having a water temperature in the floor just a few degrees above the desired room temperature to supply heating, even during design heating conditions. However, the thermal mass of the concrete slab makes this system very slow reacting, demanding a control strategy different than conventional radiant floor systems. Several studies show that conventional fast acting control systems using the room temperature sensors work poorly, especially during transition periods in spring and autumn. In the research project Lowex (Low-exergy heating and cooling), a control scheme was developed based on simple ON-OFF control, together with a linear model predictive control (MPC) taking data from weather forecasts for the next 48 hours. The linear MPC-models have been tested against measured floor slab temperatures and room temperatures during varying internal and external conditions. We found that the MPC approach works well, but parameters in the model must be adjusted for the specific usage of the building.

INTRODUCTION

Radical improvements in energy efficiency in new and refurbished buildings is needed to achieve the 1,5 °C goal in the Paris agreement (United nations Climate Change, 2021) and the climate goals of the EU (EU, 2021). Plus energy buildings are one of the most potent ways to reach this goal (Garde & Donn, 2014).

Even though an increased focus on passive measures in the European building legislation has led to a decrease in the heating demand the last decade, the same measures often increase the cooling load. Monitored high performance buildings in Norway (Langseth, 2016) show that heating- and cooling demand still dominates the energy use in buildings.

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Thermally activated buildings systems (TABS) coupled with geothermal based supply systems has the potential to provide excellent thermal comfort in buildings while reducing the demand for delivered/purchased energy to a minimum (Bockelmann, Plesser, & Soldaty, 2013). In the research project Lowex (Danielsberg & Dokka, 2021) a new concept for low exergy heating and cooling has been developed, most often with an embedded floor pipe system in concrete or screed. Low temperature heating av high temperature cooling gives the potential for extremely efficient heat-pump operation and cooling based on only free cooling from energy wells (geothermal wells). Both theoretical simulations and monitored performance of the buildings with the Lowex-concept (Dokka, Myrup, & Solsem, 2019) shows that excellent indoor thermal conditions can be achieved with this system.

One of the challenges with TABS and the Lowex concept is the slow response of the system with regard to user interventions and changes in heat gains or loads (e.g. sudden solar gain). One of the conclusions of the European Geotabs project (Bockelmann, Plesser, & Soldaty, 2013) is that conventional fast reacting control systems based on room air temperature sensors work poorly for this type of slow reacting systems, especially in the shoulder seasons (spring and autumn) where the building is in a transition between the heating- and cooling season. The main reason for this is the timelag between the thermal input (e.g. a change in setpoint) and the thermal response of the system, resulting in the input and the output of the system to be out of phase much of the time.

A new simplified model predictive control system (MPC) has been developed for the Lowex-concept to try to solve this matter. The MPC-system is based on building simulation modelling and a heat transfer model for the floor system, weather forecasting, and mass temperature sensors in the floor. The MPC-system is used to control both the central supply system of the building and the local system in rooms and thermal zones.

This paper describes the Lowex-system and the control system used on the plus energy building Powerhouse Telemark in Porsgrunn (Southern Norway) and compares predicted performance with monitored performance. The main academic contribution of this paper is to test if a simplified MPC algorithm can successfully be used to achieve good thermal comfort and very high energy performance.

CASE STUDY BUILDING

Figure 1 (a) Powerhouse Telemark as seen from south, November 2020.

Powerhouse Telemark is a plus-energy office building situated in the city of Porsgrunn, Norway. It has a total heated floor area of 7919 m2. The roof, façade and parking area are covered by 1482m2 of photovoltaic panels. The roof is sloped at a 24° angle to optimize output from the photovoltaic installation. Figure 1 shows the completed building as of November

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2020, two months after handover. One of the main objectives of the project was the achievement of Powerhouse version 1 criteria. The criteria are set by the Powerhouse partners (Stene, 2021) and are in short as follows: Renewable energy produced at the building shall offset the energy spent during the expected lifetime of the building set to 60 years, including the bound energy in building materials and the energy used during construction, commissioning and decommissioning. The criteria do not include energy for end-user equipment. Further, the indoor climate shall be conceived as being of high quality and the end users demands for functionality shall be met. In accordance with the project objectives, the design of Powerhouse Telemark aimed to achieve a seasonal coefficient of performance (SCOP) of 6 for heating, a seasonal energy efficiency ratio (SEER) of 50 for cooling, and a reduction of 80% or more in the purchased electric energy for heating and cooling of the building. Powerhouse Telemark was also designed to achieve a "Excellent" rating under BREEAM Norway (Grønn Byggallianse, 2021). To meet these objectives, the building has been incorporated with several sustainable features including ground source heating and free-cooling, and local renewable electricity production from photovoltaics (PV) panels, among others.

THE LOWEX SYSTEM

The Lowex-system is schematically shown in figure 2. In the heating season the energy wells are designed to have a supply temperature of approximately 6 °C and a return temperature of 3 °C (DT = 3 K). The supply temperature to the Lowex-system varies from appr. 22 to 28 °C during the different winter conditions, with a DT (supply-return difference) of 2,5 - 4 K. The low DT (2,5 K) are used in the transition periods spring/autumn to get a minimum flow over the condenser heat exchanger. The heat output in each room or thermal zone is controlled by ON/OFF valves based on the measured mass temperature in the floor. Setpoints for the supply temperature, the DT and the mass temperature is determined based on the MPC-algorithm described in the next section.

In the cooling season the brine fluid from the energy wells goes to the cooling heat exchanger. The supply temperature from the wells will typically vary from 6-8 °C in the start of the cooling season to 12-14 °C in the autumn. By mixing the supply with the return temperature (shunt-valve) for the lowex-system the supply temperature to the hydronic floor system is kept at approx. 19 °C. This gives a surface floor temperature around 21,5-22,5 °C during the whole cooling season (see also next section). In the cooling season all the valves in rooms/thermal zones are fully open, so there is no local regulation of the system. The cooling load of the total building is controlled by the central variable speed circulation pump which is kept at DT = 3K (return temperature of approx. 22 °C). Since we have a close to isothermal system with the floor surface only 0,5 to 3 K below the room temperature, this will act as a self-regulating system. In rooms with small heat gain (e.g. north facing rooms) the cooling output from the floor will be small. In rooms with large heat gains (e.g. direct solar gain on the floor) the cooling output can be multiple times the room with small heat gains, which is desirable to keep the rooms thermally stable. This very simple control strategy in the cooling season has shown to work very well and the practical results are well in agreement with the theoretical simulations (Dokka, Myrup, & Solsem, 2019).

In between the heating season and the cooling season spring and autumn there is a passive season where there is no circulation of water in the Lowex-system. In this "passive mode" the thermal comfort is controlled only by the ventilation system, either naturally, hybrid or mechanically. In the case of PH Telemark there is a low pressure balanced mechanical system with variable air volume controlled after the room temperature and the CO_2-level in each zone. Contrary to the slow reacting Lowex-system, the ventilation system is a fast-reacting system which works well in the transition periods spring and autumn.

The energy wells, the heat exchanger, the heat pump, the distribution system and the floor system are all designed together to achieve the low specific pump power (hydraulic performance), high COPs and high EER (thermal performance) shown in figure 2.

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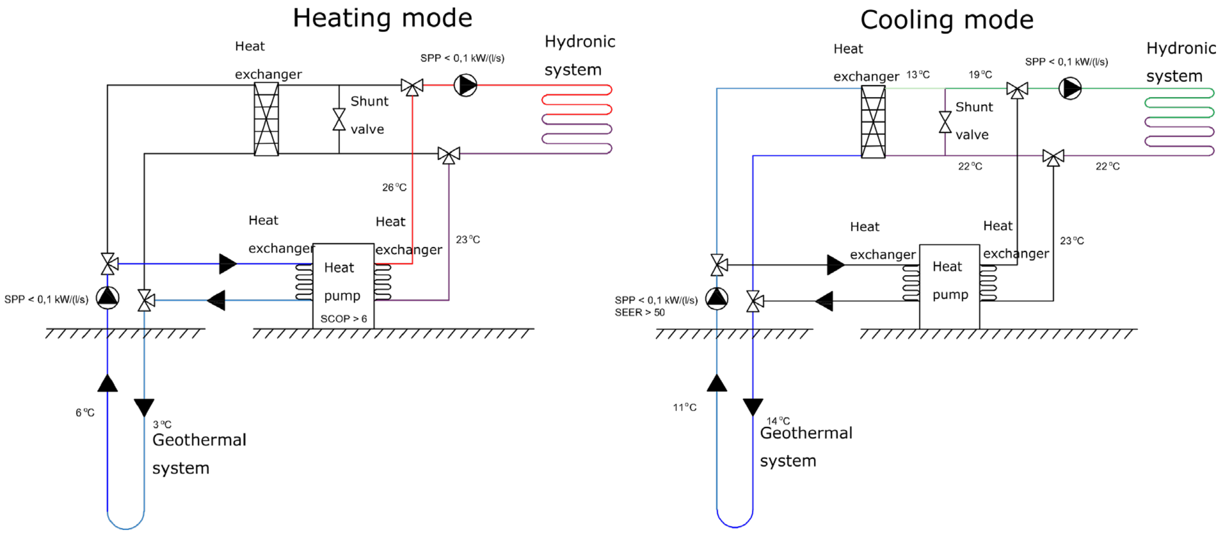

Figure 2 (a) The Lowex-system in heating mode (b) The Lowex-system in cooling mode.

Simplified model predictive control

To take into account the slow reacting response of the Lowex-system a predictive model has been developed, with the following steps:

1. A thermal building simulation model for each of the thermal zones in the building is created. This model considers heat transfer through the envelope, thermal mass, solar gains, internal gains, ventilation, etc. based on best knowledge/assumptions of the real operation of the building. The simulations are carried out for different periods during the heating season, based on the mean daily external temperature in 5 °C intervals. For PH Telemark the simulation has been carried out for mean daily temperatures for -20 °C, -15 °C, -10 °C, -5 °C, 0 °C, +5 °C and +10 °C. The heating demand for each condition is collected and used in the predictive model. The simulation is done with the dynamical simulation software SIMIEN 6.0 (Programbyggerne, 2021), which is based on an electric analogy thermal model with a timestep of 15 minutes. Simien 6.0 is partly based on the Norwegian energy calculation standard (Standard Norge, 2020) and has been validated according to EN 15265 (CEN, 2007).
2. A calculation model for the embedded flooring system based on ISO 11855-2 (ISO, 2012) is used to calculate necessary mass temperature, fluid flow, supply temperature and DT of the loop given the desired heat demand calculated in 1. This model is based on the electric analogy model given in annex B (ISO, 2012), which considers the two- and three-dimensional heat transfer in the floor slab (100 mm concrete in the case of PH Telemark).
3. Since the time-lag of a heavy floor construction could be of several hours, the mass temperature is better controlled after forecasted weather than of historical data or momentary values as are used in conventional control systems. A forecasted weighted mean temperature for the next 48 hours is used based on simulations and experience of monitored buildings (Dokka, Myrup, & Solsem, 2019). The first 24 hour forecasted temperature (0-24) is weighted with 70 % and the next 24 hours (24-28) is weighted with 30 %.
4. The simulation and calculation results of 1. and 2. are used to create linear control curves used together with the forecasted weighted mean temperature. These curves are implemented into the BEMS (Building Energy Management System) of the building and are used to control the mass temperature in the floors, the central supply temperature and the DT (supply-return temperature) of the Lowex-system.
5. The simulation and calculation in 1. and 2. is also used to calculate when the transition from heating to passive season should be done and when transition from passive season to cooling should occur. However, the MPC- algorithms used in the heating season is not used in the passive- and cooling-season. See the section above for description of the control in the cooling- and passive season.

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Figure 3, 4 and 5 show the MPC-based linear control curves used for the mass temperature, the supply temperature, the DT (supply-return) implemented in the BEMS at PH Telemark. The three curves for the mass temperature, with a parallel shift of 1 K from the base-curve A, are meant as alternative curves used to tailor the room temperature to individual desires from the occupants or to account for situations/conditions other than those assumed in the simulations (step 1.). These curves are a starting point in the tuning of the building and can and should be tuned to adapt to the real operation and desires of the occupants of the building.

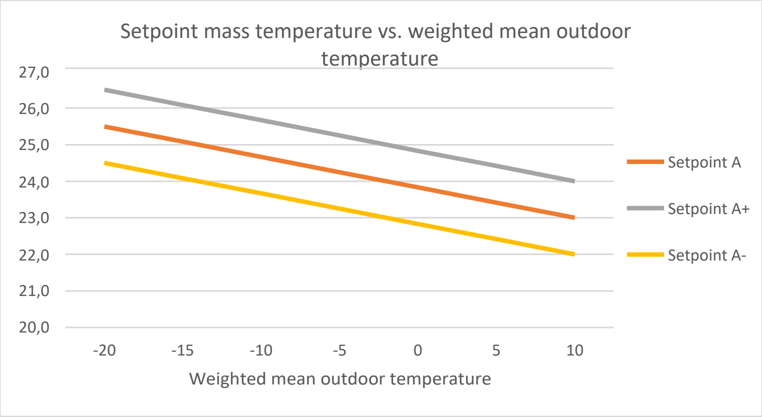

Figure 3 Setpoint mass temperature used in the heating season.

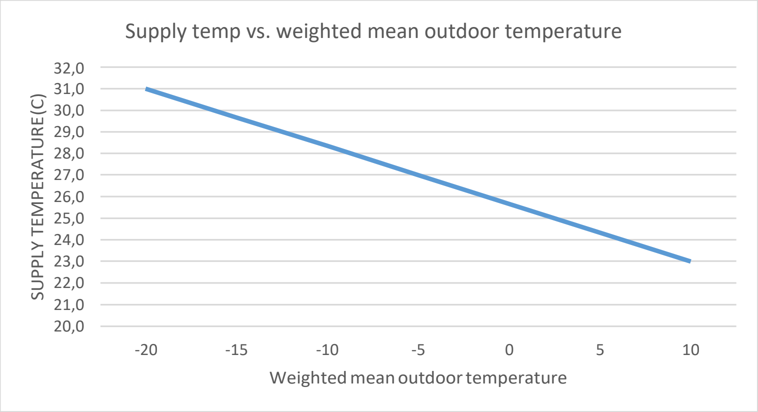

Figure 4 Setpoint supply temperature used in the heating season.

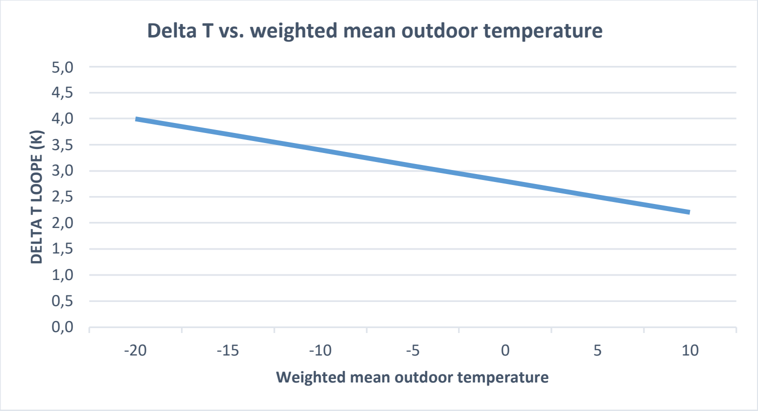

Figure 5 Setpoint delta T (supply-return) used in the heating season.

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MONITORED DATA

The building has been in the commissioning phase/trial period from August 2020 to April 2021. Due to the Covid-19 pandemic the occupant density has been much lower than planned in this period. Of the ten storeys, the 5th floor has had the highest occupant density and has been used to analyze the performance of the Lowex-system, together with data for the energy central for the whole building. Due to faults in the weather forecast-system, the MPC-algorithm hasn't been operating as planned before the start of April. The chosen period for the analysis has been taken from 5th of April to 12th of April, where the Lowex system and MPC-algorithm has been working pretty much according to the intention. This period has had cold nights but sunny days and rather high temperatures during daytime. The external temperature and the calculated weighted mean temperature are shown in figure 6. The real time external temperature varies in this period between -3 °C during the coldest nights and above 16 °C in the middle of the day. The weighted daily mean temperature (red line) is stable around 4 °C (+/- 1 °C) in this period. According to the simulation the MPC-algorithm is based on, this is still well inside the heating season of the building. Transition to the passive season is estimated (based on the simulation) to be around an daily mean temperature of 8 °C.

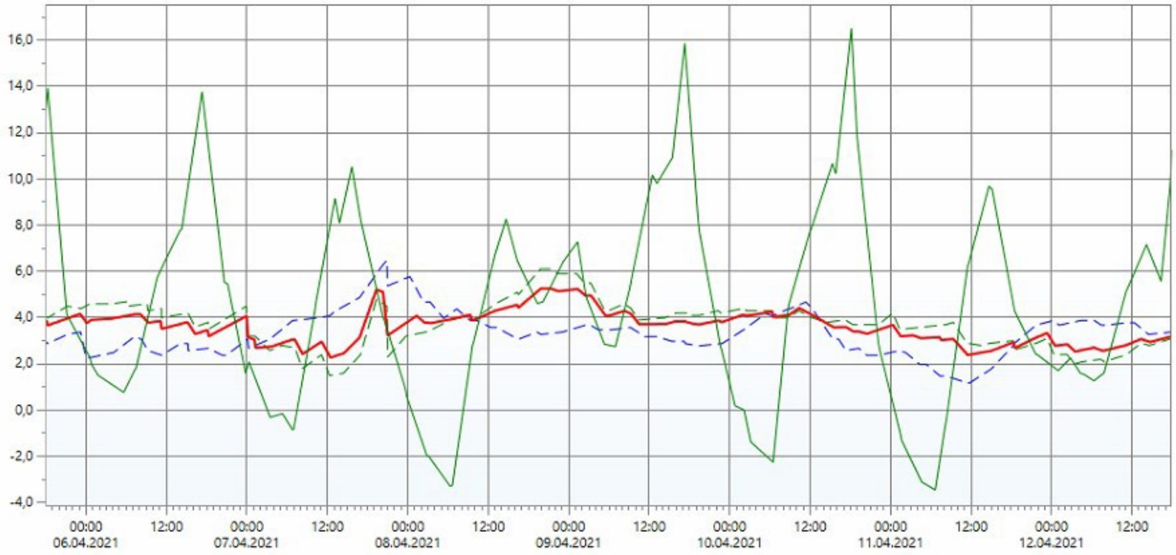

Figure 6 Data from the BEMS system in Powerhouse Telemark. Green curve is the real time outdoor temperature, green dotted curve is the first 24 hour mean, blue dotted curve is the 24-48 hours mean temperature, and the red curve is the weighted daily mean temperature the MPC-algorithm uses.

RESULTS AND DISCUSSION

Figure 7 shows the supply temperature from the heat pump going into the Lowex-system, together with the brine temperature from the energy wells. With a weighted daily mean external temperature of around 4 °C (see fig. 6), the building should, according to the MPC-algorithm, have a supply temperature of 24-25 °C (see fig. 4). However, due to the intermittent operation and the internal control system of the heat pump the supply temperature varies between 22 to 28 °C (short term spikes). However, the mean temperature is roughly in the intended range of 24-25 °C.

The temperature lift for the heat pump from approximately 7 °C source temperature and 25 °C outlet should give very good operational conditions for the heat pump. Figure 8 shows the measured COP of the heat pump during the 6th of April, and the value lies in the range 6 to 8,5 when in operation. This is in line with and even somewhat over what is expected from the heat pump under these conditions.

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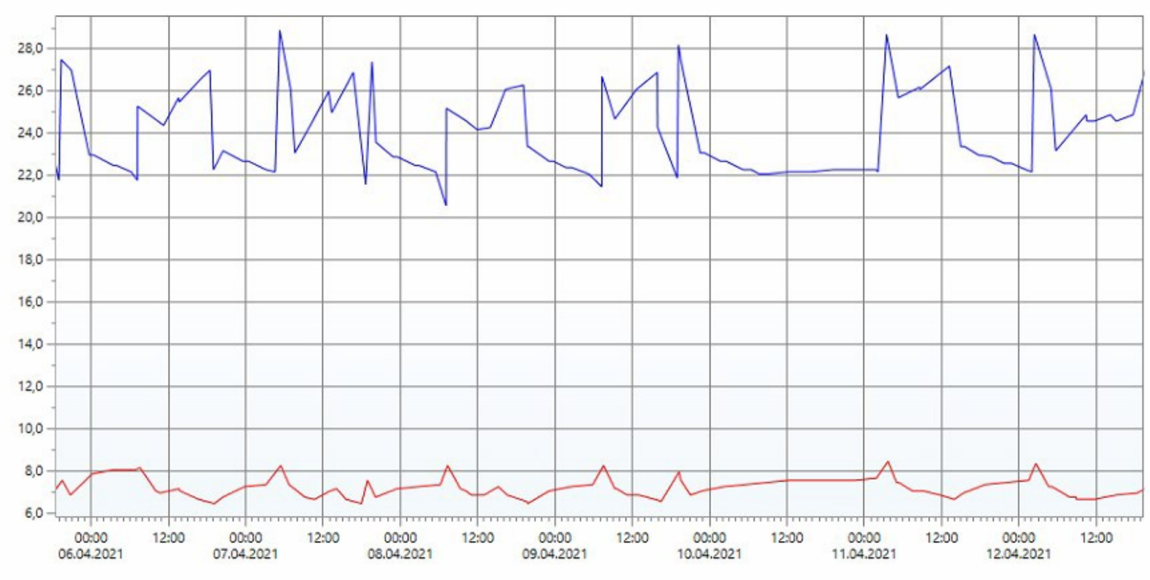

Figure 7 Data from the BEMS system in Powerhouse Telemark. Blue curve is the supply temperature from the heat pump going into the Lowex-system, the red curve is the supply temperature from the energy wells (source temperature for the heat pump).

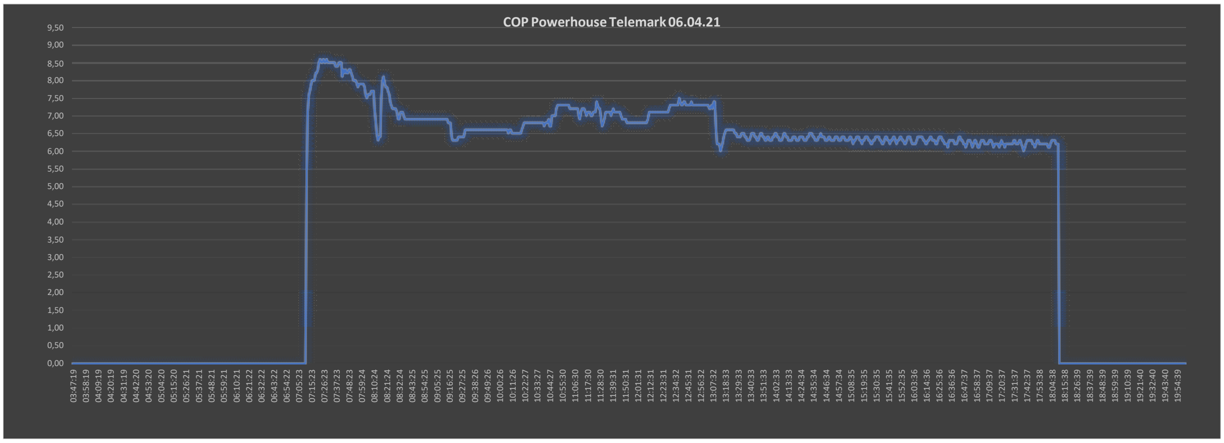

Figure 8 Measured COP of the heat pump from the BEMS-system. 6th of April.

Figure 9 shows the mass temperature setpoint, the measured mass temperature and the measured room temperature for room 519 in the 5th floor. The room is exposed for solar gains (S/E-orietation) part of the day. Other rooms and zones at the 5th floor show the same trend temperature-wise. With a weighted daily mean external temperature of approximately 4 °C, the setpoint mass temperature should be around 22,5 °C according to the MPC-algorithm with curve A (see fig. 3). The measured mass temperatures fluctuate around the set point most of the time and seem to work according to the intention. In periods the mass temperature raises higher, probably due to direct solar gains to the floor. The external solar shading for this façade is currently only occupant controlled, and the solar shading is probably not in use. This leads to somewhat high indoor temperatures in shorter periods, but not critically high. There are also operable windows in the façade that could be opened under this condition (warm inside, rather cold outside) that could cool down the room very quickly.

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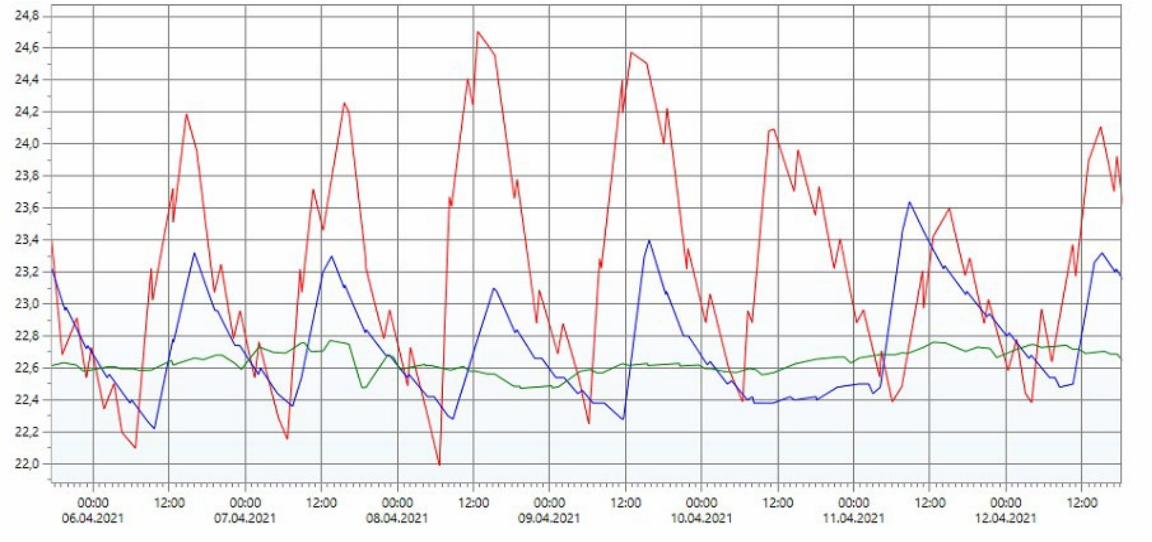

Figure 9 Data from the BEMS system in Powerhouse Telemark for room 519 (5th floor). Green curve is the setpoint mass temperature (from the MPC-algorithm), the blue curve is the measured mass temperature in floor and the red curve is the measured room air temperature.

CONCLUSION AND FURTHER WORK

The Lowex-system based on geothermal wells and high performance heat pump systems, together with low termperature heating and high temperature cooling, has the potential to be extremely energy efficient and give excellent thermal comfort year round. The Lowex-system has been implemented in the plus energy office building Powerhouse Telemark, and the system has been monitored in the end of the heating season with large diurnal variation in heat gain and heat loss. Overall, the system performs according to the intetention both with regard to energy performance with a high measured COP of the heat pump, and the thermal comfort which is also acceptable. However, fast acting systems like natural ventilation or variable volume mecahanical ventilation is desirable to assist the slow reacting Lowex-system, especially in the shoulder seasons (spring and autumn) when the heat gain and heat loss varies a lot.

ACKNOWLEDGMENTS

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NOMENCLATURE

COP = Coefficent of performance of the heat pump
SCOP = Seasonal coefficent of performance of the heat pump
EER = Energy efficiency ratio for the cooling system
SEER = Seasonal energy efficiency ratio for the cooling system

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