DEMAND-SIDE-MANAGEMENT WITH HEAT PUMPS FOR SINGLE FAMILY HOUSES

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ABSTRACT

The dynamic expansion of renewable energy production, especially solar and wind power, will accelerate the transformation process in the energy sector. In this context, the fluctuating supply of electricity based on solar and wind power units should be smoothed out to guarantee the grid stability. For this purpose, Demand Side Management (DSM) and intelligent storage technologies are key technologies that make it possible to keep the balance of supply and demand.

The objective of this study is to evaluate the fraction of residential heat demand which can be expected to be covered by using electric heat pumps coupled with an under-floor heating system as variable loads in the context of DSM.

INTRODUCTION

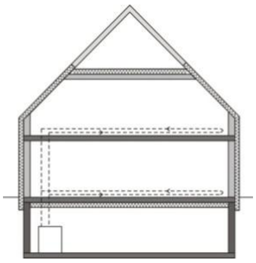
In line with the German Federal Government's energy concept, renewable energy accounts for the biggest share in the future energy mix. The crucial targets of the new energy concept are to reduce greenhouse gas emissions by 40 % by 2020 and 80 % by 2050, with 1990 being the base year for both measurements (Federal Ministry of Economics and Technology Germany (BMWi) 2010). By 2020, the share of renewables in final energy consumption is to reach 18%, and then gradually increase further to 30 % by 2030 and 60 % by 2050. The share in electricity production is to reach 80 % by 2050 (Federal Ministry of Economics and Technology Germany (BMWi) 2010). This implementation process of renewable energy represents a new challenge for the energy system not only in the national power grid, but also in local power grids.

Generally, photovoltaic panels and wind turbines feed electricity into local power grids depending on local weather conditions. Thereby, the stochastic variations of solar and wind power production make it difficult to adapt the power generation to power demand. In this context, an increasing feed-in of fluctuating renewable energy sources reduces the grid stability, which can cause in worst case seriously damage in the grid system. In order to solve this problem, it is necessary to change energy supply and consumption systems: from a demand-oriented energy generation to a generation-oriented energy consumption (Hauser 2011). Thereby, Demand Side Management (DSM) and intelligent storage technologies are the two main pillars (Schmid et al. 2010). With these technologies, the share of fluctuating electricity from renewable energy sources can be compensated, and the consumption of surplus electricity will be more flexible. In this regard, the building sector has huge potential, as the building sector accounts for about 40 % of final energy consumption in Germany (Schmid et al. 2010). In total, more than 70 % of the final energy consumed in households is used for space heating and hot water in Germany (Michelsen et al. 2011). For this reason, it is expected that the heat pump market in Germany will continue to grow in the coming years (Platt et al. 2010). Against this background, this study focuses on evaluating the thermal load shifting potential of single family houses in a local power grid. For space heating, a ground source heat pump coupled with a water-based under-floor heating system is used as a form of thermal energy storage. The potential of the thermal load shifting of heat pumps is investigated in combination with a model based predictive control system (MBPC), which is based on the study "Plus-width modulation for small-sized heat pump heating systems" by the Swiss Federal Office of Energy. The control concept quantifies optimal heating energy portions with respect to the weather forecast, the thermal behaviour of buildings and low-tariff periods (Bianchi et al. 2005). Besides the thermal load shifting potential, the evaluation of indoor thermal behaviour is also an important aspect of this study, which is investigated mainly through operative room temperature.

SIMULATION MODEL

Heat pump system and building model

The simulation model consists of a building model (single family house) coupled with an under-floor heating system, a ground source heat pump model and domestic hot water storage. The complexity of the building model is limited to a single thermal zone in order to reduce the computing time.



Construction	U-value (W/m²K)	Thermal insulation
External wall	0.27	10cm external insulation
Pitched roof	0.23	13cm roof insulation
Cellar ceiling	0.37	5cm ceiling insulation
Top floor ceiling	0.24	11cm ceiling insulation
Window	1.40	Double thermal insulating glazing

Figure 1Building model

The building model has two floors with a total floor area of 254 m². The explained building model and the heat transfer coefficients of constructions are shown in Figure 1. The design heat load calculation of the building model is based on DIN EN 12831 (DIN EN 12831 2002) that is required for the dimensioning of heat pumps. The ground source heat pump model is based on the heat pump characteristics which describe the dynamic behaviour of the heat pump, for example flow temperature dependent heating capacities as well as power consumption. The heat pump model determines thermal capacity and COP (coefficient of performance) as a function of inlet source temperature ($T_{source,in}$) from the ground model (Type 557) and outlet supply temperature ($T_{load,out}$) to the under-floor heating system of the building model. Figure 2 shows the schematic diagram of the heat pump system. The sizing of the virtual ground source and the other implemented ground parameters are based on the EED-software and VIESSMANN technical guide (VIESSMANN 2010), thus a ground model of four vertical double U-tubes of a depth of 65 m has been implemented. Besides space heating, domestic hot water (DHW) is also supplied by the heat pump with a 400 liter storage tank. The parameters of the storage tank model are taken from manufacture´s data (VIESSMANN 2012) and a 4-person based scheduled tap pattern is implemented for the storage tank. By the calculation of the design heat load, based on DIN EN 12831, a ground source heat pump model with a nominal heat output of 8.4 kW has been implemented in the simulation.

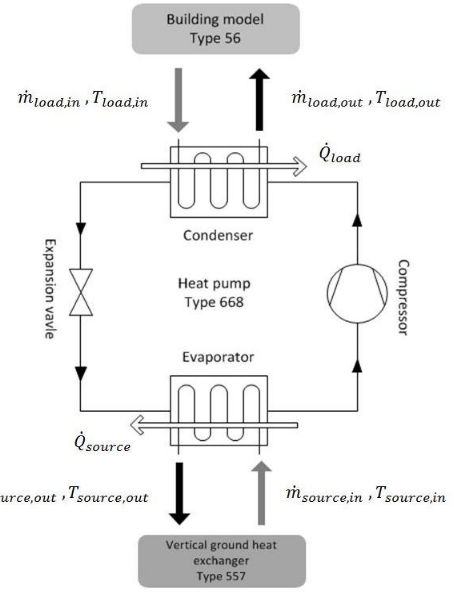


Figure 2 Schematic diagram of the heat pump system

The ground source heat pump model has a COP of 4.6 by a source inlet temperature of 0°C and a load outlet temperature of 35°C, which are based on manufacturer's data (VIESSMANN 2010).

Weather data and electricity consumption and generation

To investigate local surplus electricity supply, the electricity consumption and generation from photovoltaic panels and a planned wind farm (10MW) of the city of Wolfhagen in Northern Hessen, Germany are estimated. Besides planned 10MW wind farm, about 20 % of Wolfhagen's electricity consumption is already generated by photovoltaic panels (Morgenstern et al. 2011). The supply of local surplus electricity from photovoltaic panels, wind turbines and the heat demand in buildings, are correlated because both depend on the weather. Therefore the electricity generation by photovoltaic panels and wind turbines, as well as the meteorological input data for the TRNSYS model, were all computed using local meteorological data measured in 2007 at Bad Arolsen station, located station 20 km northwest of Wolfhagen. Logical input data for the TRNSYS model were also computed using local meteorological data measured in 2007 at Bad Arolsen. Hourly electricity generation by wind and solar power are approximated using local meteorological data on an hourly basis. These are then subtracted from concurrent household electricity consumption measurements to calculated available

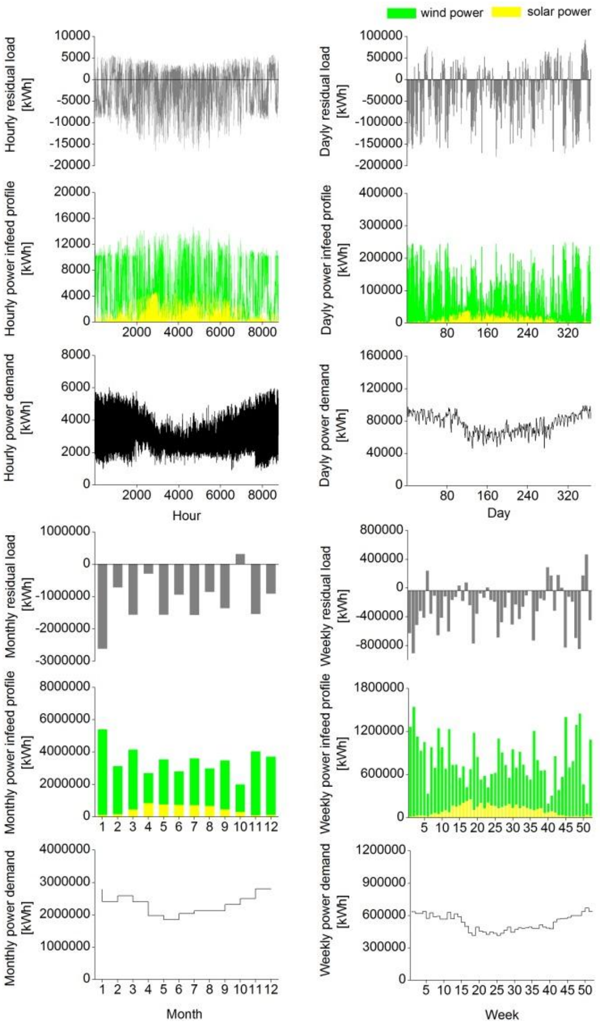


Figure 3 Renewable energy feed-in, Demand and residual loads depending on different time horizons in Wolfhagen (Hour, Day, Week, Month)

surplus electricity. Hourly values of household electricity consumption in 2007 were supplied by the Stadtwerke Wolfhagen (Morgenstern et al. 2011) (see Figure 3). Figure 3 shows the estimated fluctuations of renewable energy feed-in and power demand depending on different time horizons in Wolfhagen. In addition, graphs in Figure 3 show the resulting residual load that is defined as electricity demand minus the amount supplied by renewable energies (RE). The residual load is described by:

$$\text{Residual load} = \begin{cases} positive, \text{if } RE\ feed-in < demand & (1) \\ negative, \text{if } RE\ feed-in > demand & (2) \end{cases}$$

The graphics clearly show that nearly 100 percent renewable energy supply is possible in a annual balance through the planned wind farm and photovoltaic panels.

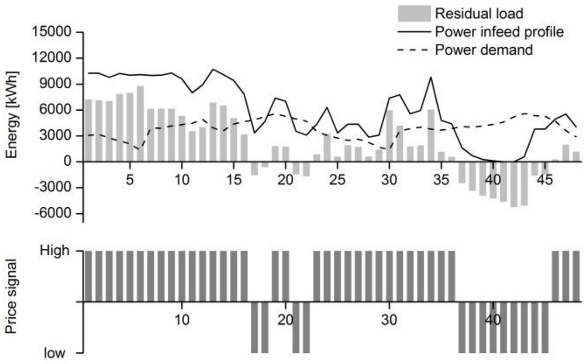


Figure 4 Electricity price signal for 48 hours in January

In contrast, the hourly fluctuations of renewable energy feed-in (wind, solar energy) in short-time horizons are very strong, so that a part of hourly power demand often cannot be covered by renewable energy feed-in. This context makes the use of short-term storage, such as thermal mass and hot water storage in buildings, coupled with DSM, more interesting.

Electricity price signal

In this study, a simple time-varying price signal is developed based on the power demand and the electricity feed-in from renewable energy sources in Wolfhagen. In Figure 4, the electricity price signal for 48 hours in January is presented as an example. Thereby, it is assumed that the local consumer can use surplus electricity with low or negative market prices. The price signal is converted into a digital signal (γ_{elec}) of codes "1" and "0" for the heat pump control. The relationship between the prices signal and the surplus electricity is described by:

$$\begin{cases} \gamma_{elec} = 1\,(low), \text{if } feed-in > demand & (3) \\ \gamma_{elec} = 0\,(high), \text{if } feed-in < demand & (4) \end{cases}$$

CONTROL STRUCTURES

Conventional heat pump control

Generally, a conventional heat pump control system is based mainly the heating curve with a dead band of ±1K, which determines the supply water temperature set-point of the heating circuit as a function of the outdoor temperature (Gruber et al. 2001). Via the heating curve, the supply water temperature of heating circuit is compensated. This control system is current practice in ground-source heat pump systems coupled with under-floor heating (Yu 2011). However, the thermal dynamics of buildings are thereby not taken into account.

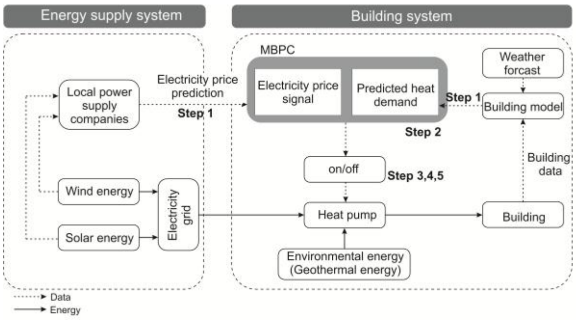


Figure 5 Basic control concept for the model based predictive control of heat pumps

As a rule, a well-insulated building equipped with an under-floor heating comprises a high thermal storage capacity that leads to a delay time between the heat supply and the response in indoor temperature (Chen 2002). Therefore, it is necessary for an under-floor heating system to take into account the thermal dynamics of buildings to compensate for the delay time and to adapt to changing dynamics. Furthermore, with the effect of time delay, the running times of heat pumps can be more flexible, which enables a heat pump to operate preferably at times when the electricity price is low. For this reason, this study focuses on the potentials of load shifting of the following control structures, which takes into account the thermal behaviour of buildings as well as electricity price signals.

Model based predictive control (MBPC)

In space heating, the predictive controller makes it possible to account for future thermal behavior of buildings. The major benefit of predictive control is that the heat supply can be adjusted in ahead for a specific time horizon due to a prediction of the future heat demand (Karlsson et al. 2011). Especially by the MBPC, a process model is used for calculating predictions of the future plant output and for optimizing future control actions (Keyser et al. 2003). In the Simulation, the building model of the dynamic thermal simulation tool TRNSYS is used as a process model for the MBPC.

In this study, the prediction of electricity price signal is additionally implemented as control input, so that the energy consumption of buildings is shifted to periods with low electricity prices through its thermal capacity. This concept makes it possible to integrate the heat pump operation of private houses into the local electricity grid without penalizing the indoor thermal comfort. The basic control concept is shown in Figure 9. The time horizon of a control period is called the prediction horizon (N), and the prediction of heat demand is computed through the building model (TYPE 56) of TRNSYS, which is based on the transfer functions by Mitalas and Stephenson (Stephenson et al. 1967).

For the control system, an identical building model is used both in predictions and operation of heat pump, i.e. the prediction is identical to the realization. Furthermore, it is assumed that the prediction of weather and electricity price is perfectly matched to realization. Instead of the setting of the flow temperature set-point via the heating curve, the optimal operation of heat pump in terms of electricity prices can be defined with respect to the future thermal behaviour of buildings. Thereby, the required heat energy is transformed into on-off switch signal for the heat pump and it regulates energy flow to the building. For this purpose, the following steps are carried out:

Step 1: Future heat demand over a prediction horizon is computed by using a weather forecast (ambient temperature and solar radiation) and a building model, and the available amount of the surplus electricity for the heat pump operation is computed depending on the given prediction of electricity prices.

· In the simulation, it is assumed that in the future electricity price profile is known in advance at least for a prediction horizon.

· By the calculation of the available amount of the surplus electricity for the heat pump operation, it is assumed that the heat supply to the building is constant during operation of the heat pump.

Step 2: The MBPC compares the future heat demand and the available amount of the surplus electricity over a prediction horizon.

Step 3: The future heat demand is transformed through the plus-width modulation (PWM) concept into on-off switch signal for the heat pump. It regulates energy flow; depending on electricity price signal.

Step 4: When the available surplus power over a prediction horizon is enough to cover the future heat demand over a prediction horizon, the heat pump is switched on only in the phase of low electricity prices.

Step 5: When the required amount of energy is covered through low electricity prices, the heat pump is finally switched off.

At the beginning of this study, it is assumed that the reference prediction horizon of 24 hours can cause high room temperature fluctuations due to the long term thermal load shifting. In contrast, it enables a flexible heat pump operating depending on electricity price signals that causes better matching with electricity price signals. Therefore, it is essential to investigate different time intervals of the prediction horizon by MBPC. In order to investigate influences of the different time intervals of prediction horizon on the behaviour of room temperature and thermal storage, it is useful to look closer at the division of

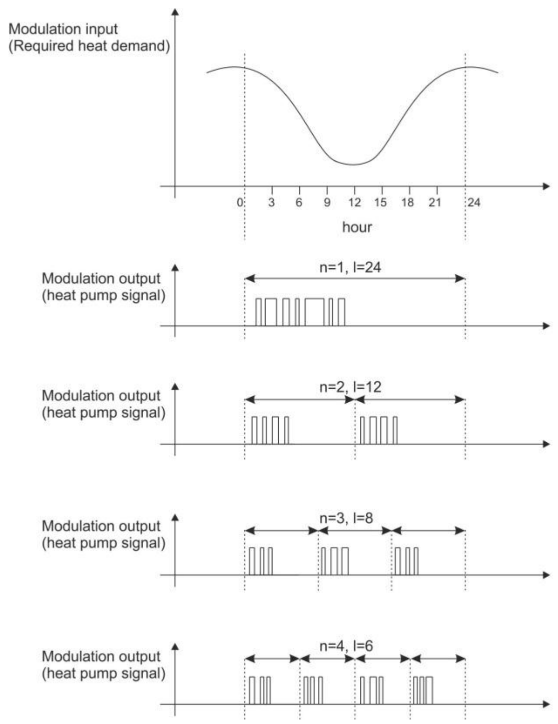


Figure 6 Pulse width modulation with different time interval of the prediction horizon

the prediction horizon into the different time steps. Therefore, the reference interval (L: 24 hours) is divided in to n small intervals of length l. Figure 6 illustrates this partitioning of the four prediction horizons, which are used in the simulations.

The time step of the prediction horizon is described by:

$$L=(n_j+n_j+1......) \qquad j>0 \tag{5}$$

Beside the MBPC with a fixed time interval of the prediction horizon, a MBPC with a varying time intervals of the prediction horizon is investigated in this study. In this algorithm, the both information, 24 hour-future heat demand and 24hour-electricity price prediction, are used to identify a suitable prediction time interval from 6 hour prediction interval to 24 hour prediction interval. In this process, a short time interval has the priority in order to minimize the temperature fluctuation. For example, the 6 hour prediction interval will be preferred selected if the surplus electricity is enough available over the day. In contrast, the 8, 12 or 24 hour prediction interval will be selected if the surplus electricity is only available only in a given period of time. In this case the heat pump will be operated with long term thermal load shifting. In the end, these control structures will be compared to a conventional heat pump control system.

Heat pump efficiency

The efficiency of heat pump operation is described by the seasonal performance factor (SPF), which is defined as the ratio of seasonal heating output by electricity consumption of the whole system during a period. In principle, different balance boundaries for both input and output energy are possible depending on system configuration (Miara et al. 2010). In this study, both thermal energy production for space heating and DHW are outputs and energy consumption of the pumps (the brine pump and the pump of heating circuit) and the heat pump are inputs to the energy balancing of SPF.

In order to assess the influence of heat pump control systems on heat pump efficiency with regard to load shifting, it is necessary to define which kind of energy is referred to the heat pump. The heat pump efficiency can be increased with an increasing share of renewable energy (surplus electricity). In this regard, heat pump efficiency is also assessed through the seasonal primary energy efficiency factor (SPEEF) in order to quantify the renewable consumption. Equation (6) describes the conventional seasonal performance factor. In comparison to equation (6), equation (7) describes the seasonal primary energy efficiency factor (SPEEF) in which the rate of renewable energy consumption is subtracted from the entire energy consumption. So, the SPEEF especially takes account for the power consumption from fossil energy sources.

$$SPF=\frac{Q_{heat}+Q_{dwh}}{P_{hp}+P_{bp}+P_{cp}} \tag{6}$$

$$SPEEF=\frac{Q_{heat}+Q_{dwh}}{P_{hp}+P_{bp}+P_{cp}-P_{re}} \tag{7}$$

Q_{heat} : *Heat consumption for space heating*
Q_{dwh} : *Heat consumption for domestic water heating*
P_{hp} : *Energy consumption for the heat pump*
P_{bp} : *Energy consumption for brine pump*
P_{cp} : *Energy consumption for charge pumps*
P_{re} : *Renewable energy consumption for the heat pump and pumps*

Control variations

Table 1 Control variations

Model 1 :Conventional control system with a heating curve
Model 2 : MBPC (24 hour-Prediction horizon)
Model 3 : MBPC (12 hour- Prediction horizon)
Model 4 : MBPC (8 hour- Prediction horizon)
Model 5 : MBPC (6 hour- Prediction horizon)
Model 6 : MBPC (Variable prediction horizon)

In this study, six heat pump control variations are simulated and assessed in terms of heat pump efficiency and indoor thermal behaviour. The six control variations are listed in Table 1.

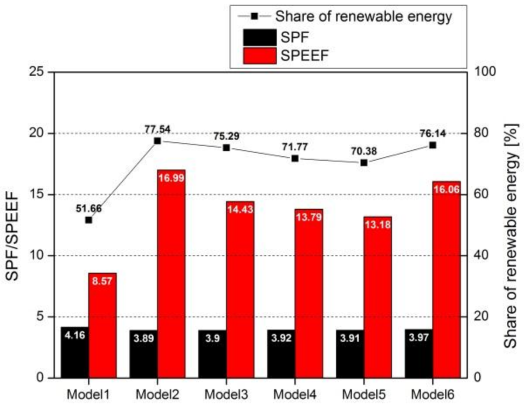


Figure 7 Seasonal performance factor (SPF), seasonal primary energy efficiency factor (SPEEF) and the share of renewable energy

RESULTS AND DISCUSSION

Energy efficiency

Figure 7 shows both the seasonal performance factor (SPF) and the seasonal primary energy efficiency factor (SPEEF) of the different heat pump control structures. The SPEEF of Model 1, which operates the heat pump depending on outdoor temperature, amounts to 8.57. In this case, the share of renewable energy amounts to around 51 %. In comparison to Model 1, the share of renewable energy of the heat pump control structures (MBPC) ranges between 70 % and 76 %. Consequently, the SPEEF of the heat pump control structures are also highly increased and the values range between 13 and 16. In contrast, the SPFs are reduced slightly. This can be explained by increased heat pump running time. In the analysis of heat pump operation with MBPC, it has been found that a long time interval of the prediction horizon often extends heat pump running time (see Figure 8) that raises flow temperature of the heating circuit. This process reduces consequently both COP and SPF. On the other hand, the comparison of the results of Model 2, 3, 4 and 5 demonstrates that a long time interval of the prediction horizon in the calculation of SPEEF makes heat pump operating more flexible and enables more renewable energy consumption. Besides Model 2, using an optimized time interval of the prediction horizon (see Model 6) also enables a high share of renewable energy in heat pump operation.

Indoor thermal behaviour depending on operation characteristics of the heat pump

This section yields a detailed description of the operation characteristics of the heat pump in terms of renewable energy consumption and resulting operative room temperature.

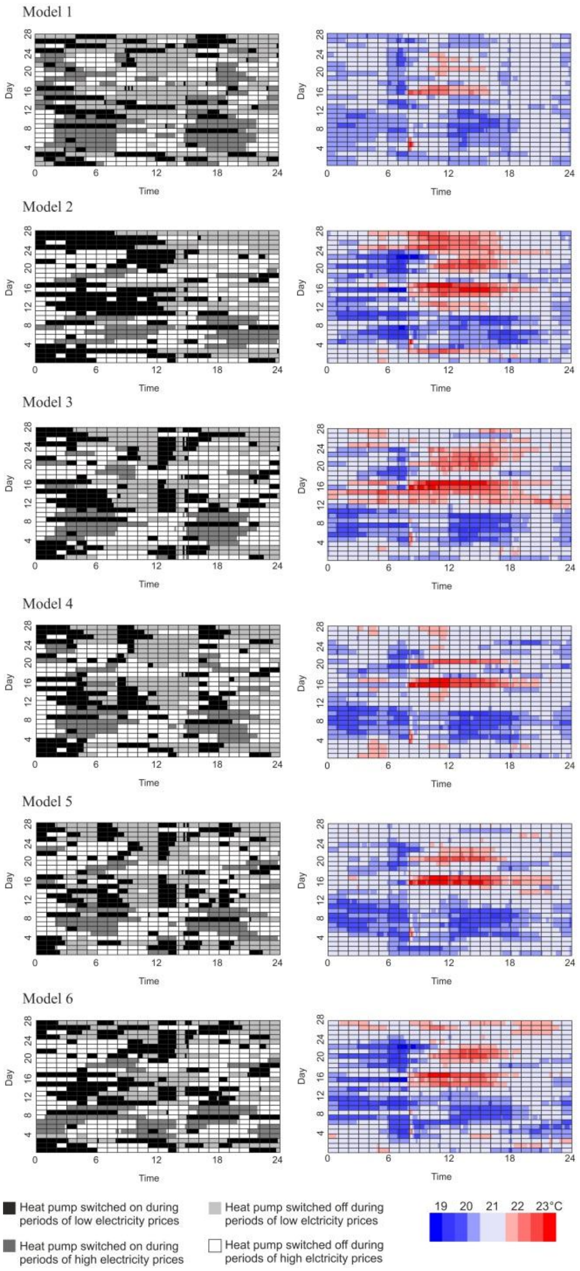


Figure 8 *Carpet plot diagram to investigate status of heat pump operation in terms of surplus electricity consumption (left) and operative room temperature (right) in February*

The operative room temperature, which is approximated in the room centre as the mean value of the radiant temperature from surrounding surfaces and the room air temperature, is used as an evaluation criterion for indoor thermal behaviour.

The operative room temperature and status of heat pump operation, which represents operation characteristics of the heat pump, are presented in carpet plot diagrams that describe values at each intersection of rows (day) and columns (time) during a month. In Figure 8, the left diagrams show status of heat pump operation depending on the electricity price signal.

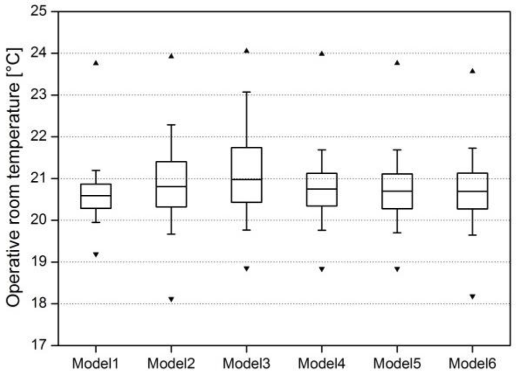


Figure 9 Box plot diagram for distribution of operative room temperature during heat pump operation in winter season
▲/▼ : Maximum / Minimum
lower and upper bars : 5th /95th percentiles
lower and upper outlines of the box : 27th/75th percentiles
line in the box : mean value

Thereby, special attention should be paid to the black shaded area as it indicates the match between the electricity demand of the heat pump and the supply profile of surplus electricity. The figure reveals clearly that the long term prediction interval (see Model 2) allows flexible heat pump operation depending on electricity price signals which increases the rate of surplus electricity consumption. In this case the estimated heat demand is mostly covered by long term thermal load shifting.

The right diagrams show the resulting operative room temperature that ranges between 19°C and 23°C. Most of the time, the operative room temperature in the case of Model 1 is kept between 20 and 22 with low temperature fluctuations. In comparison to Model 1, it is demonstrated by the results of Model 2-6 that MBPC can be used to shift the energy consumption to periods with low electricity prices.

Additionally, the results of the operative room temperature show that the load shifting control strategy (MBPC) increases overheating hours. The comparison of the results of Model 2-5 shows that the short-term interval of the prediction horizon limits the surplus electricity consumption, additionally it decreases overheating hours. The result of Model 6 shows that the surplus electricity consumption is highly increased through a varying time intervals of the prediction horizon by MBPC. In this case, the SPEEF rises up to 16.6, as well as the share of renewable energy rises up to 76.14 %, (see Figure 7). Otherwise, the right diagram shows that overheating hours are slightly reduced in comparison with Model 2 and Model 3 through using optimized time intervals from the prediction horizon for MBPC.

Additionally, the distribution of operative room tempeature for three winter months (from December to February) is represented as a box-plot diagram in Figure 9. It is used as a quantitative quality indicator for the analysis of indoor thermal behaviour. In this diagram, special attention should be paid to the Model 3. The share of overheating hours is higher than Model 2, although the time interval of the prediction horizon is shorter than Model 2. This can be explained by the starting time of the second period of the prediction horizon. In the case of Model 3, the second period starts at noontime, where solar heat gain through windows is high. In this case, the heat pump is operated with a long running time, although there is only a low heat demand. This can be prevented if the period time of prediction horizon is reduced, (see Model 6). To summarize, Model 6 satisfies the two main criteria: on the one hand, the load shifting effect is maximized; on the other hand, the influence of load shifting on the indoor thermal behaviour is minimized.

Conclusion

This paper discusses the potentials of heat pump operation and its control systems in terms of DSM and thermal load shifting. The performance of the different control structures has been investigated. The results of the simulations show that the MBPC significantly increases coordination between heat load and energy generation, thus the share of surplus energy for space heating is increased, in the best case, by up to 50%, compared to a conventional control system. Furthermore, the results show that the room temperature fluctuation by load shifting can be reduced by use of optimized time intervals on the prediction horizon.

From a user's perspective, the control structure (MBPC) in combination with DSM provides significant energy saving potential by heat pump operation coupled with under-floor heating systems. However, this kind of energy saving is only possible if the slight temperature fluctuation is by user-allowed. At the same time, the load shifting with heat pumps has a positive effect on grid stabilization.

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