Control Strategies for Geothermal Heat Pump Systems in Combination with Thermal and Electrical Storage Units

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Abstract

The European Commission requires all new buildings to be nearly zero energy buildings (nZEBs) by the end of 2020. NZEBs are characterized by very high energy performance and low energy demand that is covered mostly by renewable sources. Although building envelopes and technical equipment for nZEBs already exist, intelligent control strategies are not yet defined. Thus, there is a risk of missing the nZEB targets. This paper describes a control strategy for plus energy terraced houses using renewable sources: photovoltaics (PV) and heat pumps as well as thermal and electrical storage. The results show how to control the heat pumps in order to increase the self-consumption of PV. The control strategy increases the direct consumption of PV by 21 %.

Introduction

Since the German *Energiewende* (2014a) began, nearly zero energy buildings in the building sector have been in focus. Recently, the researche on nZEBs was mainly focused on the definitions of nZEBs. Hernandez et al. (2010a) gives a definition and evaluation methods for nZEBs. Berthelmes et al. (2015a) described building design and construction and Kibert (2010b) showed system configuration. The low energy demand and use of PV in nZEBs require a heating technology that enables integration into the energy grid. Heat pumps are suitable for use in nZEBs because low exergy systems, e.g. floor heating, with a low temperature level are used. Fadejev et al. (2016a) show the potential of heat pumps with different heat sources in an nZEB. The heat sources examined are boreholes, energy piles, and thermal storage units. The combination of the heat sources consisting of 60 energy piles, 2 boreholes, and a solar collector yielded the lowest energy consumption of the nZEB. Although heat pumps and PV have been installed in the building sector in the past few years, the interface and interaction between the components are hardly clarified. As a result, an energy efficient operation mode of all components is not ensured. This is also discussed by Franco et al. (2016b). They describe the interaction between heat pump, PV plant, and grid in a residential building during an experimental analysis in order to maximize the self-consumption and the efficiency of the heat pump. The results of the study show a low efficiency of the heat pump and the dependency of self-consumption on an advanced control strategy.

This research was designed to integrate various energy generators and energy storage units with a demand side management system (DMS) into plus energy terraced houses. The plus energy terraced houses are characterized by a yearly positive energy balance. The energy for the terraced houses is delivered by a PV plant that supplies more energy than the house needs in a year. There is a surplus of 10 % PV production in relation to the consumption. The aim of the research is the efficient control of the heat pumps in order to increase the self-consumption of the PV plant, using an intelligent DMS. In this sense, self-consumption means the part of the PV production per year, which is consumed by the heat pumps and the households of the terraced houses directly. The DMS controls eight terraced houses that are supplied by a common geothermal heat pump system. In addition, the geothermal heat pumps are connected in parallel and able to modulate the compressor speed. Decentralised domestic hot water heat pumps (DHW-HP) are integrated in each terraced house to provide domestic hot water. Besides the thermal storage units, there is an electrical storage for storing the surplus PV production after fulfilling the electrical demand of the household and heat pumps. The complex interaction between design parameters and control settings will be discussed in this paper.

Methods

Control strategy

The DMS is intended to maximize the self-consumption of the PV plant as well as to control the heat pumps in the most energy efficient way.

The order for satisfying the demand by PV depends on the flexibility of the consumer. Figure 1 shows the flow chart of the control strategy. First, the inflexible consumers like household electricity, ventilation, and other electrical auxiliary energy are provided by PV production. The modulating heat pumps (MHPs) and the DHW-HPs have a lower priority because they can adapt to the available amount of PV electricity. In addition, the thermal storage units allow flexibility for taking advantage of temperature limits. The thermal storage units can both store surplus energy and serve as a bridge until the next PV production phase.

The storage for heating demand consists of a storage cascade of two thermal storage units. They include an 800 litre buffer storage and 2000 litre surplus storage, which

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is only active during PV production. A low temperature level at 35 °C is set in order to increase the coefficient of performance (COP) of the MHPs. As the MHPs are able to adjust the speed, the DMS can adapt the speed of the heat pumps to the PV power. This results in an increase of PV exploitation and a reduction of additional grid power by bridging the gap between PV productions.

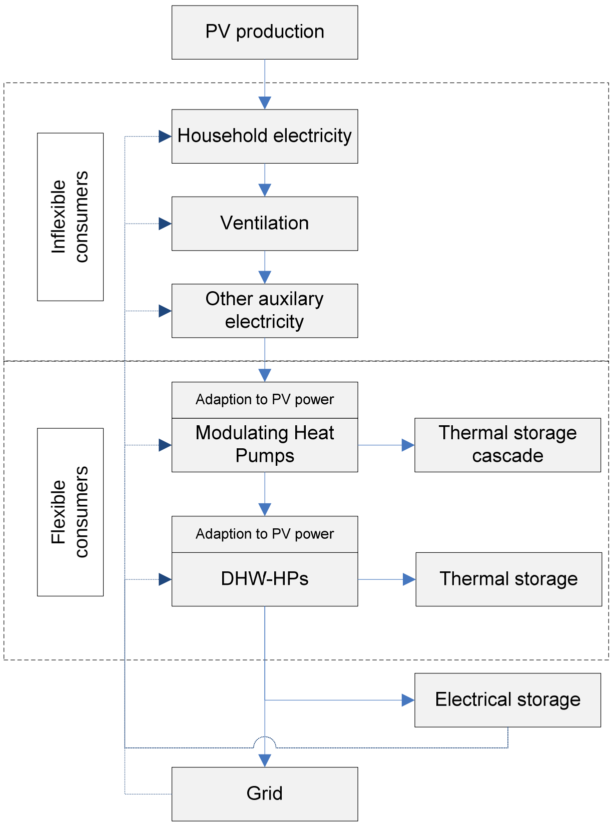

Figure 1: Flow chart of control strategy

The supply of domestic hot water is decentralised in each terraced house via a DHW-HP and a 200 litre water storage unit. As the DHW volume is small, the water will be renewed daily. This prevents a legionella contamination of the DHW system. Regarding the advantages of energy efficiency, the water-water-HPs use the thermal storage cascade as a heat source. The domestic hot water demand is determined by DHWcalc (2010c), using a cumulative probability method. The advantage of eight small DHW-HPs is the temporal different loading process through different user behaviour that leads to a reduction of electrical load peaks. Moreover, the eight small DHW-HPs can adapt to the PV production in a row and the self-consumption of PV can be increased. During PV production the DHW-HPs charge the storage units at a higher temperature level of over 65 °C.

Modulating heat pumps

A possible method to increase the direct usage of the PV production onsite is the adaption of the HP power. Besides this PV optimized operation, the modulation also has a benefit of energy efficiency. Due to the HP inverter performance characteristic, a COP optimized operation can be realized in part-load operation. Figure 2 shows a high efficiency (max. COP) at a modulation speed of 40%. The presented control strategy optimizes the speed of the two heat pumps with respect to the COP and the actual produced PV power.

Due to a lack of modulating simulation models for heat pumps in TRNSYS, the existing TRNSYS Type 401 from Afjei and Wetter (1997) was extended and validated for modelling the modulating heat pumps. Type 401 is a grey-box-model that represents the heating up and cooling down behaviour of the heat pump with a power and COP correction. The correction is made with the solution of the first order differential equation (PT1-theory). The model does not describe the internal refrigerant cycle, internal controller, valves, and thermostats. For the capacity control, the presented adapted version (Type 4010) uses the normalized inverter frequency (modulation speed). By introducing the modulation speed, the bi-quadratic-polynomial equation for describing the heat pump characteristics can be derived with a higher accuracy. Equation (1) shows the new polynomial equation (P_i) with eight coefficients (bq_n), an evaporator inlet temperature ($\varphi_{x,ev,in,i}$), a condenser outlet temperature ($\varphi_{x,cond,out,i}$), and the modulation speed ($Y_{n,i}$). The result (P_i) of equation (1) is represented by using different polynomial coefficients, the thermal and the electrical power of the heat pump.

The capacity of the MHP Type is controlled either by an external controller or by an internal Type. Two different internal control modes are available: (i) return temperature control and (ii) PV power control. In the control mode (i), the heat pump power is a function of the return temperature (condenser inlet temperature) and in control mode (ii), it is adapted automatically by speed modulation according to the available PV power. For the automatic speed modulation, the Type uses equation (2), which is a polynomial equation with evaporator inlet temperature ($\varphi_{x,ev,in,i}$), condenser outlet temperature ($\varphi_{x,cond,out,i}$), and the available PV power ($P_{PV,av}$).

In order to link the Type in TRNSYS, two additional inputs ($Y_{n,i}$, $P_{PV,av}$) and three parameters ($Mode_C$, $P_{el,HP,min}$, $P_{el,HP,max}$) are required (see Table 1).

Compared to the measurement data of the manufacturer, the MHP Type represents the condenser, compressor, and electrical power with very small deviations. The RMSE values between measurement and simulation are 0.1072 to 0.7026 (see Table 2).

$$\begin{aligned} P_i &= bp_1 + bp_2 \cdot \varphi_{x,ev,in,i} \cdot Y_{n,i} + bp_3 \cdot \varphi_{x,cond,out,i} \cdot Y_{n,i} \dots \\ &+ bp_4 \cdot Y_{n,i} + bp_5 \cdot \varphi_{x,ev,in,i} \cdot \varphi_{x,cond,out,i} \cdot Y_{n,i} + bp_6 \cdot \varphi_{x,ev,in,i}{}^2 \dots \\ &+ bp_7 \cdot \varphi_{x,cond,out,i}{}^2 + bp_8 \cdot Y_{n,i}{}^2 \end{aligned} \tag{1}$$

$$\begin{aligned} Y_{n,i} &= bp_1 + bp_2 \cdot \varphi_{x,ev,in,i} \cdot P_{PV,av} + bp_3 \cdot \varphi_{x,cond,out,i} \cdot P_{PV,av} \dots \\ &+ bp_4 \cdot P_{PV,av} + bp_5 \cdot \varphi_{x,ev,in,i} \cdot \varphi_{x,cond,out,i} \cdot P_{PV,av} + bp_6 \cdot \varphi_{x,ev,in,} \\ &+ bp_7 \cdot \varphi_{x,cond,out,i}{}^2 + bp_8 \cdot P_{PV,av}{}^2 \end{aligned} \tag{2}$$

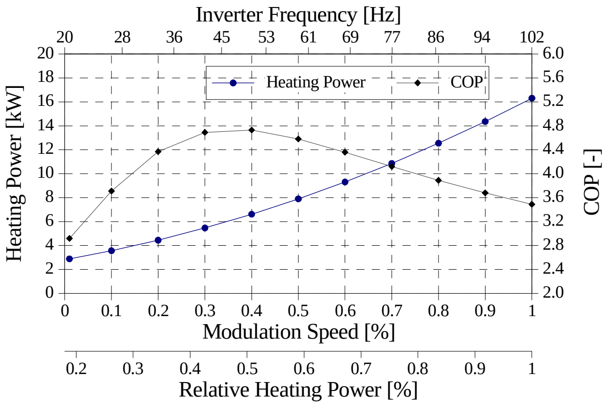

Figure 2: Heating power and COP over the modulation speed, inverter frequency, and relative heating power of the heat pump

Table 1: Additional inputs and parameters of MHP Type 4010

Input $Y_{n,i}$	modulation speed of the MHP
Input $P_{PV,av}$	available PV power
Parameter $Mode_C$	modulation control mode
Parameter $P_{el,HP,min}$	min. required electrical power for HP operation
Parameter $P_{el,HP,max}$	max. electrical power for HP operation

Table 2: Validation data of the MHP –RMSE values

evaporator power	0.6326 kW
compressor power	0.1072 kW
condenser power	0.7026 kW

Simulation

In order to verify the targets of the DMS for modulating heat pumps, the terraced houses and the heating system are modelled in the simulation program TRNSYS (2015b). The modular structure of TRNSYS allows a high flexibility for modelling building structures and plant systems. Each technical component is represented by a Type and is connected to other Types by in- and outputs. As the terraced houses are built in Northern Bavaria, Germany, the weather data from the test reference year for region 13 (2014b) was chosen. The simulation period is one year with a time step of 5 minutes.

Building and boundary conditions

Type 56 was used for modelling the terraced houses. Each terraced house has 5 zones, including cellar, ground floor, upper floor, top floor, and an attic. In total, the building model has 40 zones. Table 3 shows the geometric data for the building envelope of each terraced house. The u-values of the exterior walls differ from the insulating material used in the houses. Table 4 gives a summary of the u-values for all exterior components. The floor heating is modelled as an active layer in TRNSYS. The set room temperatures are defined according to DIN EN ISO 7730.

During the heating period, the room temperatures are between 20 °C and 22 °C. The heating period is defined by an average outside air temperature over 24 hours of under 8 °C, and for summer above 12 °C. In the summer period, the set room temperatures are from 22 °C to 24 °C. Table 5 shows boundary conditions for infiltration, ventilation, heating, and cooling as well as internal gains.

Table 3: Geometric data of each terraced house

length	10.99 m
width	6.44 m
height without cellar	11.49 m
floor area	153 m²
volume	558 m³
angle of roof	40 °

Table 4: U-values of the terraced houses

floor	0.17 W/m²K
ceiling	0.16 W/m²K
wall	0.13 – 0.18 W/m²K
window	0.70 W/m²K

Table 5: Boundary conditions

infiltration	0.04 1/h
air change	0.4 1/h
effectiveness	80 %
heating	active layer
cooling	active layer
internal gains	45 kWh/m²*a

The terraced houses show a typical performance for highly insulated houses according to heating and cooling demand. Table 6 gives a summary of heating, cooling, and DHW demand of the terraced houses. The cooling demand is nearly three times higher than heating demand. The household electricity is determined by the program, Loadprofile Generator (2016c), that offers the possibility to take various devices and schedules into account. The load profiles vary for each terraced house depending on a 2 to 6 person family household. In total, the electrical load profile adds up to 33,400 kWh per year for all eight terraced houses. Table 7 gives a summary of the electrical consumption of the terraced houses.

Table 6: Heating, cooling and DHW demand of terraced houses

heating	10,642 kWh
cooling	30,534 kWh
DHW	22,788 kWh

Table 7: Electricity consumption of terraced houses with DMS

household electricity	33,400 kWh
ventilation	1,412 kWh
other auxiliary electricity	9,658 kWh
MHPs	5,196 kWh
pumps for heat/cool	1,704 kWh
DHW-HPs	5,705 kWh
pumps for DHW	165 kWh

Design Aspects

A previous simulation study investigated the interaction between design parameters, control settings, and energy consumption. The study examined the sizing of battery and thermal storage as well as the temperature level of the thermal storage and its impacts on the grid consumption of the terraced house including the household electricity. As the main part of the investigation, a parametric study combined different sizes of battery and thermal storage and temperature levels. The battery capacities were 40 kWh, 50 kWh, and 60 kWh. The sizes of thermal storage included 3.2 m³, 5.3 m³, 6 m³, and 7.2 m³. The temperature levels were 35 °C, 45 °C, and 55 °C. The parametric study produced 36 combinations and results. Figure 3 shows the dependencies for the different storage volumes (3.2 – 7.5 m³), electrical storage capacities, and set point temperatures in the buffer storage tanks. A good energy efficiency is characterized by configuration with a high electrical storage capacity and a low set point temperature in the storage tanks. The buffer storage volume itself does not have a large impact on the results.

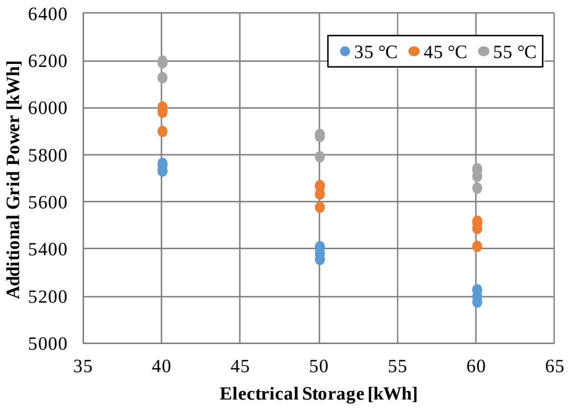

Figure 3: Dependencies of capacity of electrical and thermal storage and set point temperature

Another result of the design study is the identification of optimal cost and energy efficiency of the storage capacity for the battery system. In this investigation, the battery has a capacity from 0 kWh to 60 kWh with 10 kWh steps, while the thermal storage size is 2.8 m³ and the temperature level is 35 °C. Figure 4 shows that the grid consumption can be reduced significantly by 41 % to reach a battery size of 40 kWh. Between the maximum size of 60 kWh and a size of 40 kWh is only an additional 8 % reduction of grid power while costs increase by 40 %.

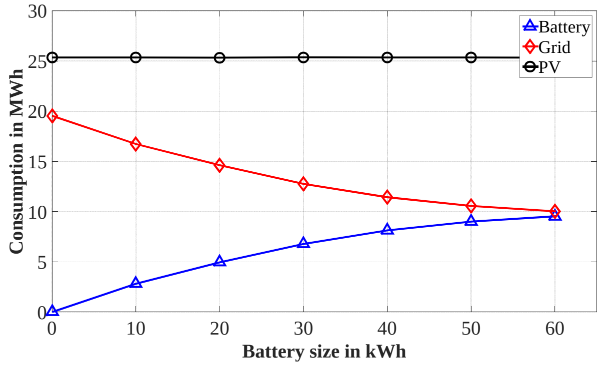

Figure 4: Surplus PV production and size of the electrical storage over grid consumption

Modelling

The consumption that is not influenced by the DMS is determined in a separate simulation and Type 9e imports the data file during the simulation. This concerns the demand for heating, cooling, and DHW as well as electrical demand for household electricity, ventilation, and other auxiliary consumers, e.g., building control and electrical bathroom radiators.

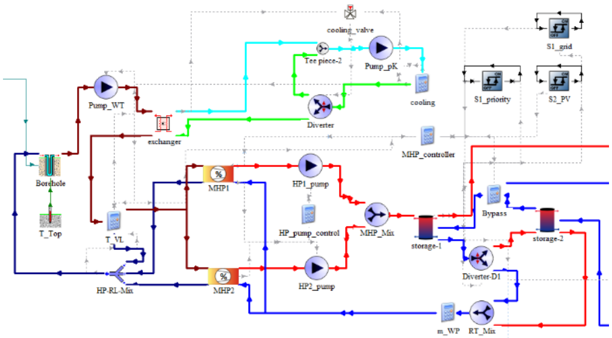

Figure 5: Detail of geothermal heat pump and thermal storage system in the TRNSYS model

Types that are connected to each other represent the technical components. Figure 5 shows a detail of the geothermal heat pump and thermal storage system modelled in TRNSYS. The MHPs are represented by the new Type 4010. The specifications for the polynomial are from the manufacturer's data sheet. The maximal heating power is 17.21 kW under conditions of B0/W35. The storage cascade consists of two Types 534 without heat exchangers. Each storage unit is separated into 5 layers. The loss coefficient is selected as 0.3 W/m²*K for edges, bottom, and flue. To set the temperature level in the storage units, the controller Type 2b is used. The source for the MHPs is a geothermal heat exchanger (GHX) represented by Type 557a. A heat exchanger for passive cooling is between the GHX and MHPs. Type 91 is used for the heat exchanger with an effectiveness of 0.9.

The model of the domestic hot water heat pumps and thermal storage system consists of 5 DHW-HPs and 5 thermal storage units because, except for houses 1 and 2, the same load profile is shared between pairs of terraced houses. Figure 6 shows a detail of one DHW-HP in the TRNSYS model. Type 401 is restricted to two Types in each simulation model. Therefore, the DHW-HPs are modelled in an equation by calculating the polynomial. The specifications for the polynomial are from the manufacturer data sheet. The maximal heating power is 2.6 kW under conditions of W20/W65. To model the DHW storage, Type 60 k is used. The tank coefficient 0.3 W/m²*K is selected. The heat exchanger is not used.

The electrical production and storage systems comprise a PV plant, orientated to east and west, a battery, and an inverter. Figure 7 shows a detail of the electrical production and storage systems modelled in TRNSYS. Type 94a is selected for PV. The parameters are from the manufacturer data sheet for the 300 W panel. The PV production is 61,737 kWh per year under the weather conditions of the test reference year for region 13. The battery is represented by Type 47a with parameters for a capacity of 39.5 kWh and a charging efficiency of 0.9. Type 48a is used for the inverter with regulator efficiency and inverter efficiency at 0.97. The charging fraction limits are from 0.2 to 1. The maximal power capacity is 18 kW.

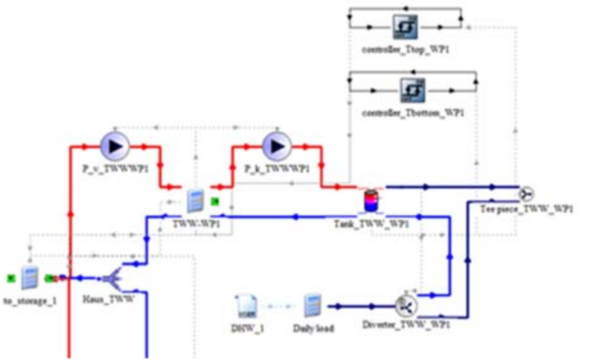

Figure 6: Detail of one domestic hot water heat pump and thermal storage system in the TRNSYS model

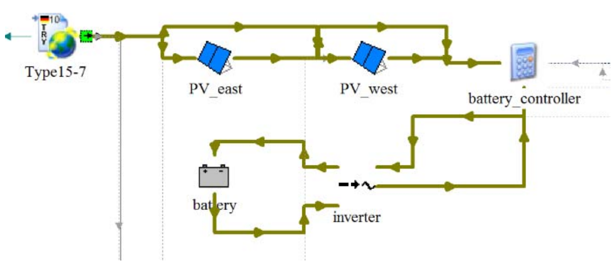

Figure 7: Detail of electrical production and storage system in the TRNSYS model

DMS Implementation

The DMS controls the heat pumps in order to increase PV consumption and reduce consumption of additional grid power. Therefore, the DMS also influences the temperature level of the thermal storage units. During PV production, the temperature level of DHW storage units increases from 50 °C to 65 °C. The temperature level in the thermal storage cascade is 35 °C during the heating period. During PV production, the surplus storage is also charged by the MHPs. In the cooling period, the heating demand is restricted to the DHW. The inlet temperature for the DHW-HPs is limited to a minimum value of 20 °C. For that reason, only the first storage unit is charged and it has a lower temperature of 30 °C.

The speed of the modulating heat pumps depends on the polynomial that is described by the inlet temperature of the evaporator, the return temperature of the condenser, and the power of the compressor. In order to adapt the compressor power to PV supply, the available PV power is used in the polynomial instead of the compressor power. Figure 8 shows the speed in relation to the PV power level for an evaporator inlet temperature of 5 °C and a condenser return temperature of 35 °C.

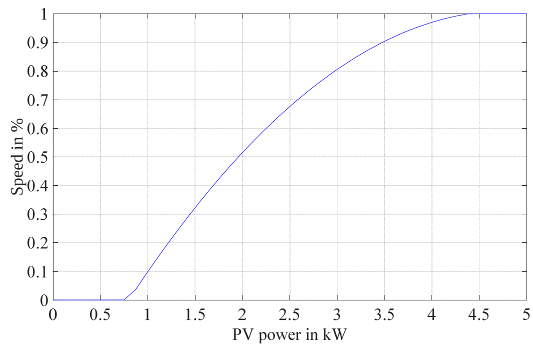

Figure 8: Polynomial for adapting the speed of MHPs

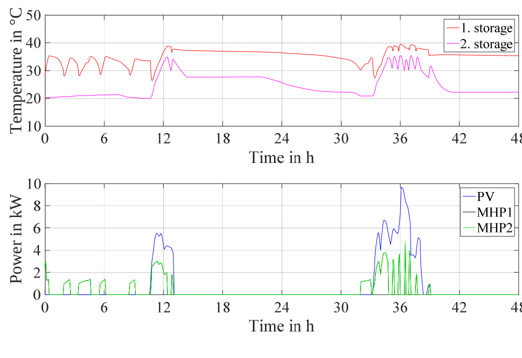

Figure 9: Adaption of MHPs to PV power during a period of 48 hours

Figure 9 shows the adaption of MHPs to PV power over a 48-hour simulation period. To reduce the battery and grid consumption, the MHPs decrease the speed to 0.4 because the best COP is between a speed of 0.3 and 0.4, as shown in Figure 2. To comply with the supply temperature of the floor heating, the storage temperature has to be higher than 27 °C in storage 1. If the temperature sinks under 27 °C in storage 1, the speed increases to 0.8, even under PV conditions.

To evaluate the developed control strategy, a basic variant with a standard control strategy is simulated. The basic control strategy consists exclusively of a heat-controlled operation of heat pumps. This has an impact on the hydraulic structure and the temperature in the storage units. Without the PV control, the heat pumps do not adapt to PV production and the temperature in the thermal storage units and the DHW storage units does not increase during PV production. Thus, the heat pump type and the second surplus buffer storage tank are changed in a new TRNSYS plant model. The basic variant uses on-off speed (Type 401) for the geothermal heat pumps instead of modulating heat pumps. In this case, the second surplus storage is not used and is superfluous without a PV control strategy. Therefore, the first thermal buffer storage tank with a volume of 800 litres, also presented by Type 534 without a heat exchanger, is the only thermal buffer storage tank in the basic variant. The DHW-HP System has the same hydraulic structure, but the control does not require increasing the temperature in the storage during PV production.

Results

In this section, the simulation results from the basic control and the DMS are compared. Important values for evaluating the DMS are the efficiency of the heat pump systems and the self-consumption of PV. The efficiency of the heat pump system can be described by the seasonal coefficient of performance (SCOP). The coefficient gives the ratio of heating power to electrical power over the year. An energy efficient heat pump system has a high SCOP. The SCOP of both geothermal heat pumps increased from 4.5 (on-off speed) to 5.3 (modulating speed). This is an effect of the higher COP due to the modulation of the heat pumps between a speed of 20 % and 70 %.

The SCOP of the DHW-HPs decreased from 4.2 to 3.9. This effect results from the lower COP at the higher temperature level in the DHW storage units during PV.

Figure 10 compares the self-consumption of the PV plant and the basic variant. The direct consumption increased by 21 %. The battery feed decreased by 10 %. This is an effect of the increased direct consumption and less surplus afterwards. Nevertheless, the grid feed decreased by 11 %.

Figure 11 shows the self-sufficiency of the terraced houses. The DMS increased the consumption of PV by 21 %. The purchase of additional grid power was reduced by 13 % and the battery consumption decreased by 10 %. The reduced battery consumption is also an effect of the increased direct PV consumption, which, in turn, means less feed to the battery.

Another result of the DMS is the contribution to the grid integration of nZEBs. In comparison to the basic variant, the load peaks decreased from a maximum of 32 kW to 24 kW. This is a reduction of the maximum peak load by 24 %. Figure 12 shows the grid consumption by the terraced houses during a time period from January until March with and without the DMS. The reduction of load peaks and grid consumption as well as the decreased grid feed from PV show the impact of the terraced houses for stabilizing the grid.

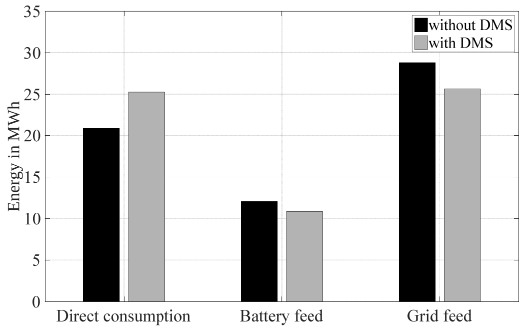

Figure 10: Self-consumption of PV plant

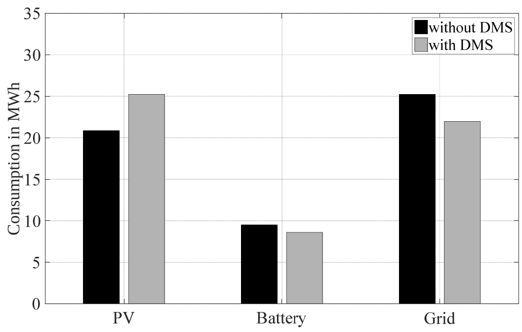

Figure 11: Self-sufficiency of terraced houses

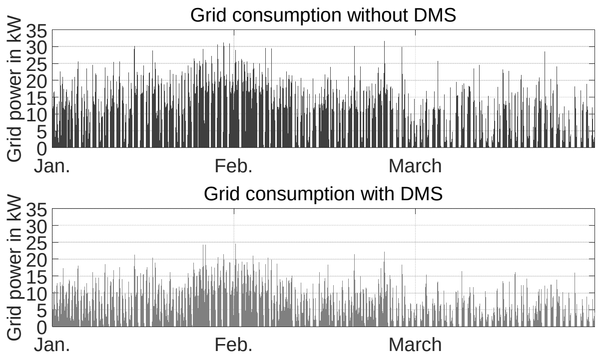

Figure 12: Grid consumption from January until March with and without DMS

Conclusion

Modulating heat pumps in plus energy terraced houses requires the development and use of an effective control strategy. This paper presents how to develop and use a control strategy for modulating heat pumps in plus energy terraced houses. The aim of the DMS is the control of

MHPs and DHW-HPs in order to increase the self-consumption of PV. Thermal and electrical storage units are used to increase the flexibility of heat pumps. The DMS adapted modulating heat pumps to PV production by controlling the compressor speed.

To model a modulating heat pump in TRNSYS a new Type 4010 was created.

To evaluate the potential of the DMS, the terraced houses and the plant were built in the simulation program TRNSYS. A basic variant with a standard heat-controlled operation was compared with a DMS controlled version. The simulation results showed an increase in the self-consumption of the PV plant of 21 %. The DMS increased the consumption of PV by 21 % and reduced the consumption of additional grid power by 13 %. The usage of battery decreased by 10 %. In general, the DMS increased the SCOP of the MHPs from 4.3 to 5.3 compared to a basic control strategy. The SCOP of the DHW-HPs decreased from 4.2 to 3.9 because of the higher temperature level.

Another result of the DMS is its contribution to the grid integration of nZEBs. The DMS reduced the maximum load peak by 24 %. Reducing the grid consumption and the PV feed as well as the maximum load peak show the impact of the terraced houses on stabilizing the grid.

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Abbreviations and Terms

COP	-	*coefficent of performance*
DHW	-	*domestic hot water*
DHW-HPs	-	*domestic hot water heat pumps*
DMS	-	*demand side management system*
HP	-	*heat pump*
Energiewende	-	*nuclear phaseout*
MHPs	-	*modulating heat pumps*
nZEBs	-	*nearly zero energy buildings*
PV	-	*photovoltaics*
SCOP	-	*seasonal coefficent of performance*

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