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HIGHLY EFFICIENT AND FLEXIBLE POWER PLANTS IN BUILDINGS

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ABSTRACT

This paper investigates a new system for balancing the electrical grid by using dynamic simulation. It consists of a fuel cell that runs continuously to achieve high efficiency. To have the possibility to react to fluctuations in the electrical grid, the system additionally contains a certain number of heat pumps that use the electrical energy provided by the fuel cell, if it does not need to be fed into the grid. Thus, the system generates and consumes power while keeping the grid in balance. The system can achieve energy savings compared to a combination of gas boilers and a gas turbine of up to 33 %.

INTRODUCTION

Heat applications in buildings are responsible for a big amount of energy consumption in Germany. 35 % of the final energy consumption in Germany is spent on space heating and domestic hot water supply in buildings (Ziesing, 2011). If a reduction of the German final energy consumption is aspired, the heat supply of buildings has to become more efficient.

Besides the heat supply of buildings, also the electricity generation in Germany is changing towards a more renewable supply of electrical power. Upcoming renewable energy sources like photovoltaics and wind fluctuate in their generation due to a dependency on the weather. These fluctuations lead to a need for bigger capacities of fast reacting power generators. They can deliver energy if the renewables are not able to satisfy the demand in the electrical grid.

At the moment, basically big central power plants work as those fast reacting power plants. This leads to several problems. In those plants, the produced waste heat of the power generation process is often not used. Thus, the overall efficiencies of those plants are low compared to a solution with heat usage. The production in central power plants can also lead to bottlenecks in the electrical grid, as too much power has to be transported over the transmission lines. From the power plants to the consumers, losses of electricity (e.g. transformers, cables) have to be considered additionally. Due to these aspects, a decentralized possibility for electrical power supply should be analysed.

This paper will analyse a high-temperature fuel cell (type SOFC) which runs with temperatures of up to 750 °C (Huijsmans et al., 1998). Thus, it is not recommended to switch it on and off too often as heating up and cooling down take a long time. The considered fuel cell has a very high electrical efficiency of about 60 % (Obernitz, 2012) and it is also possible to use a part of the waste heat for space heating and domestic hot water supply. At the moment, these micro-chp units based on a fuel cell feed their total production into the grid. In times when there is a high feed-in of renewables in the electrical grid, this could cause problems because of a disbalance between generation and consumption.

To utilize the fuel cell with its high efficiency for future systems with high rates of renewables in the grid, it is possible to combine the fuel cell with several heat pumps to one power generating unit. The heat pumps are located in vicinity to the fuel cell and can use some of the generated electricity to generate heat. If enough electrical power is generated by renewables, the fuel cell should not feed additional electrical energy into the grid. In this case, the heat pumps are turned on. The heat pumps are used to modulate the power output of the total system based on on/off-signals which come from the electrical grid. The generated heat can be stored as well as the thermal energy which is produced by the fuel cell. Therefore, this is a flexible and energy-efficient power plant which will be analysed in detail in the following sections. This power plant consists of two types of buildings. In one type the fuel cell operates and in the other type a heat pump is generating heat in times when the elctricity is not needed in the grid.

With this approach, the problem of storing electrical energy is partly converted to a problem of storing thermal energy. Thermal storages are much cheaper than electrical storages and this can lead to a greater usage of thermal storages in terms of balancing the electrical grid compared to what we have now.

First, the used model of the building, the systems engineering and the control strategy is presented. Systems engineering here describes all heat generating units (fuel cell, heat pump, boiler) and the storage. An external signal which can be seen as an indicator for the generation from renewables is used to control the heat pumps. For the generation of the signal, a methodic approach is presented. The generated signal is used by the control strategy of the heat pumps. Then we analyse to what extent the shown system can supply buildings with enough heat for a whole year. Due to the fact that it is recommended to save as much energy as possible, an analysis of the used fuel in comparison to a reference system consisting of decentralized gas boilers and centralized electricity generators is done. This paper is a first study to evaluate the potential of such decentralized systems.

MODELLING

The used model consists of different parts. All these parts are modelled in the object-oriented description language Modelica (Modelica Association, 2010) with the tool Dymola (Dassault Systems, 2013). Many parts of the models (especially the ones concerning the building) are taken from the Modelica libraries developed at our institute (Hoh et al., 2005). As stated before, there are two different models that are used to investigate the system. The first model is representing the electricity-producing part and the second model is representing the electricity-consuming part of the system.

The electricity-producing part includes the fuel cell, a thermal storage, space heating and domestic hot water generation. A scheme of this model is shown in Figure 1. The fuel cell should operate continuously. This means that it is connected to a thermal storage and loads it all year round. The system consisting of the fuel cell and the storage is designed in a way that a peak-load-boiler is not needed and the fuel cell can supply the building with enough heat for space heating and domestic hot water. This means, that a certain part of the heat has to be wasted in times when the heat demand is not high enough which can especially happen in summer. The domestic hot water generation is modelled by a tap water station which is directly connected to the storage. The storage is also the basis for supplying the building with enough heat for space heating. The space heating demand is characterized by the mass flow rate, flow and return temperature of the total building.

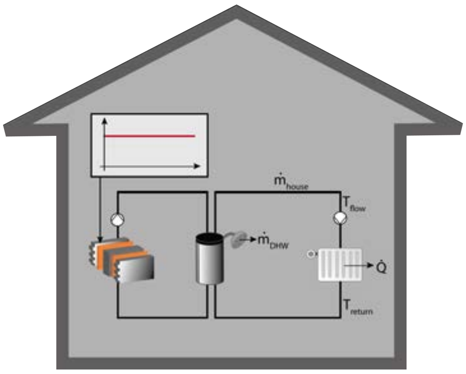

Figure 1: Scheme of the system with a fuel cell.

The electricity-consuming part is a model consisting of a heat pump, a peak-load boiler, a storage and again the space heating and the domestic hot water. A scheme of this model is shown in Figure 2. The heat pump is controlled by an external signal which is not continuous because of the demand from the electrical grid. If the heat generated by the heat pump and stored in the thermal storage is not sufficient, a peak-load-boiler is used to generate the additional heat. The single parts of the system will be presented in the following.

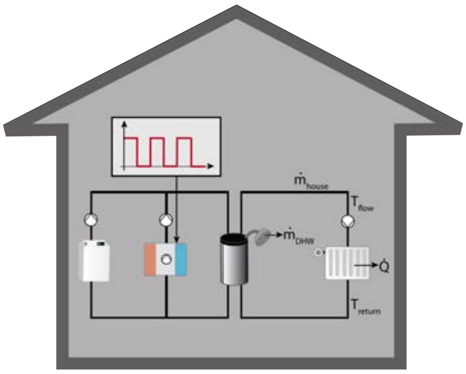

Figure 2: Scheme of the system with a heat pump.

Building

Both the fuel cell and the heat pumps run in single-family houses. As a first approach, all considered buildings are assumed to be the same. This building is modelled as detailed as possible. For this, we use Modelica to model a single-family house which has a very high insulation standard. All walls and windows are geometrically represented and the user behaviour (air exchange rate, internal gains) is also considered with constant values. The model of the building is completely equipped with a radiator including a thermostatic valve in every room. With this, it is possible to consider the whole building system. More information about the modelling of the building is provided in (Müller and Badakhshani, 2010) and (Lauster, 2012). The considered building has a maximum heat load of 4.7 kW, is located in Germany in the TRY-region 12 (Deutscher Wetterdienst DWD, 2011) and has a total heat demand for space heating of about 4900 kWh per year. The annual load duration curve of the building heat demand is shown in Figure 3.

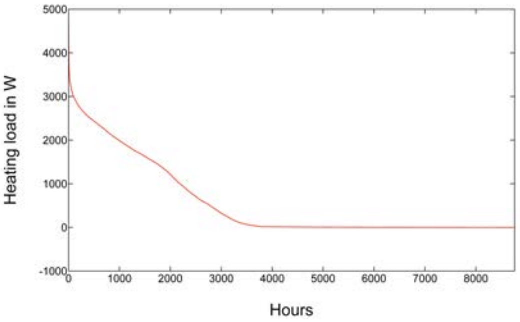

Figure 3: Annual load duration curve of the considered building.

We want to analyse systems with more than one building and our focus in this paper is not in the interaction between the building and the systems engineering. Furthermore, we will analyse the entire system with different boundary conditions given by the electrical grid. This means, we analyse the behaviour of the systems engineering with a given response of the building and the varying requirements of the electrical grid. For simulations with many buildings, simulation times are getting very big if all buildings are represented totally. There is a need for measures to improve the simulation speed.

Thus, we simulate a detailed model of the house with an ideal boiler only once. In this model we gurantee that the desired room temperatures in the building are reached for the whole year and with this, a certain thermal comfort can be guaranteed. At night (between 22 o'clock and 6 o'clock), the set temperature in the building is 17 °C and during the day (6 o'clock to 22 o'clock), the set temperature is 21 °C. For the supply temperature, we use a heating curve for the flow temperature as a function of the ambient temperature of the building. From this simulation, we used the flow and return temperatures and the mass flow rate of the whole building and use this as a input in form of a table for the simulation of the systems engineering in every house. So the temperatures and the mass flow rates which the building needs to satisfy its demand are considered and influence the operation of the storage.

This gives us a further advantage besides increasing the simulation speed. The room temperatures in the house can vary with different systems engineering if the interaction of the systems engineering with the thermal mass of the building is also considered. Different flow temperatures can occur which would result in different heat flows from the radiators to the building and varying indoor air temperatures for different simulations. This does not occur in our model. All considered variants have exactly the same boundary conditions given by the building. As long as we are not interested in the building as a storage which can store energy in its thermal mass or the influence of different user behaviour, this is an appropriate procedure. With a system simulation with 12 ”houses”, heat pumps and storages, the simulation time was about eight hours. In comparison to this, the total simulation of the single building with the ideal boiler needed a time of more than one day.

Fuel Cell

The fuel cell is modelled as a simple heat source that can load the storage to supply the building with heat. Fuel cells with an electrical efficiency of about 60 % are currently available on the German market (Obernitz, 2012). This fuel cell has an electrical power of 1.5 kW and a thermal output of about 560 W in its operating point. Fuel cells are built up modularly with stacks. Thus, higher capacities are possible if several identical stacks are combined to a bigger unit. Due to this, we assume the fuel cell to be completely scalable. In this paper, we analyse a fuel cell which has an electrical power of 12 kW. The electrical power of the regarded fuel cell is eight times the power of the original cell. The thermal power of the cell is also multiplied by eight (results in a thermal power of 4.48 kW). This fuel cell can deliver enough heat for the building all year round if it runs continuously and loads the storage. Occasionally, more heat is available than can be stored or used. As maximum reachable flow temperature of the fuel cell 70 °C is assumed. If the temperature would increase above this temperature assuming a constant heat source, this surplus heat will leave the fuel cell through the chimney without any usage.

Heat Pump

The considered heat pump is a speed-controlled air-to-water heat pump. The reason for this is that we want to be able to modulate the electricity-consumption when it is running. If the heat pump was operating with a constant speed, it would not be possible to guarantee a constant capacity in operation, because the electrical power would depend on the conditions like source temperature and sink temperature. The model is adapted from (Huchtemann et al., 2013). It is based on a polynomial approximation for the compressor. Using polynomial functions the model calculates the electrical and the thermal power. The polynomial functions are dependent on the source and the sink temperature as well as the compressor speed. We took a heat pump which can guarantee an electrical power of 3 kW. Thus, we need four heat pumps running at once relating to the electrical power of the fuel cell to balance the grid.

Storage

As storage, a stratified buffer storage is used. The modelling approach is taken from the buffer storage model published in the Modelica library ”Buildings” (Wetter, 2009). In contrast to this model, in our model no components of Modelica Fluid are used. Instead of this, equations for the heat transport using enthalpy flows based on mass flow rates and temperatures are formulated. A mass flow which enters in the entry layer with a certain temperature and exits at the exit layer with the temperature of this exit layer transports enthalpy through the storage between entry and exit. Every layer has a certain heat capacity according to its dimensions. The energy transfer between the layers considers the enthalpy flow through loading/unloading of the storage, the heat conductance and the fluid transfer due to a non-perfect stratification. This means, that a heat flow from a lower to a higher layer is calculated considering bouyancy effects. In addition, the heat transfer to the environment is calculated by a heat transfer coefficient.

It is possible to have several connection ports for loading and several connection ports for unloading. In our simulations, we use one connection pair (top and bottom of the storage) for loading. In the first building, the fuel cell is connected to the storage, in every other building there is one heat pump connected to the storage. On the demand side of the storage, two unloading circles are connected, one for space heating and one for domestic hot water. Both the loading and the unloading cycles are directly connected to the storage without a heat exchanger. For the standard case, a system with a storage of 1000 litres for all heat pump systems is assumed. The building with the fuel cell is equipped with a storage of 2500 litres. The storages are bigger than in actual standard systems, because the heat cannot be generated at any time but only in certain phases. In this time, the system should store as much energy as possible. The chosen volumes of the storages are not optimized for the system but we assume it to be an adequate approach to analyse the system.

Consumer

Based on the building model, the model for space-heating is developed. The mass flow rate to the building, flow and return temperatures are taken from the building simulation. With this data, a detailed simulation of the system is possible. If the temperature in the storage is above the desired flow temperature, we can calculate a mass flow rate that is needed from the storage to satisfy the energy demand of the building. For this, we assume that a mixing valve from the return temperature is present and can be used to regulate the flow temperature exactly. If the temperature is less than the desired flow temperature, an ideal boiler fills the gap between the storage temperature and the desired flow temperature. The produced heat of the boiler is assumed to be generated with an average efficiency of 95 % (Wolff et al., 2004). For the domestic hot water supply, a tap water station is modelled. It is built up as a counterflow heat exchanger. The water is flowing from and to the storage on one side and on the other side, water with an assumed temperature of 10 °C enters the heat exchanger and then goes to the consumer. The temperature of the domestic hot water has to be 45 °C at the outlet. The heat exchanger is assumed with a heat transfer coefficient of 1200 $\frac{W}{K}$. If the temperature coming from the storage is too low, again the ideal boiler is used to generate the extra heat on the supply side of the heat exchanger with an efficiency of 95 % (Wolff et al., 2004). The tapping profiles are generated with a special software called DHWcalc (Jordan and Vajen, 2005) for a temperature of 60 °C. Those profiles are converted into profiles with a temperature of 45 °C. All considered buildings in this paper have an identical load profile in heating as well as in domestic hot water tapping profiles. The domestic hot water demand mentioned in this paper is about 4250 kWh per year and is therefore 46 % of the total heat demand.

Control

The system we are analysing is designed to balance the electrical grid. Thus, we have to use a methodology to analyse such systems. This paper presents a first approach to implement a generic method. This method is based on on/off-signals which are sent to the heat pumps.

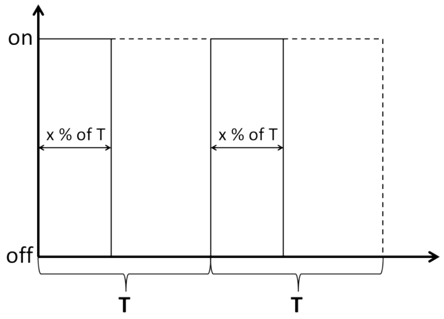

Figure 4: Scheme of the general control of the heat pumps, shown for two time periods T.

Figure 4 shows the general procedure of the generation of the signal profiles for the heat pumps. We assume a time period T which determines a periodical behaviour. The whole year is divided into time frames with the length of T. A certain percentage x of this time span T the signal is ”on”, after that time period, the signal switches to ”off” until the end of T. After T has ended, the process repeats for another T. The signal ”on” means that the heat pump has to be switched on because the fuel cell should not feed electricity to the grid at that time.

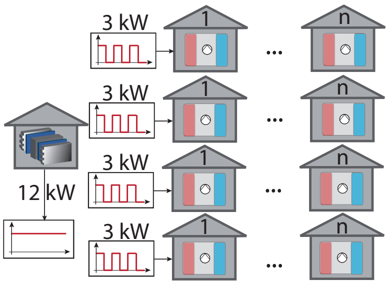

Figure 5: Total evaluated system with fuel cell and heat pumps and their operation.

The fuel cell is designed with an electrical power of 12 kW and is running continuously around the year. The considered heat pumps should run with an electrical power of 3 kW. Thus, we have a need of four heat pumps running at once if the signal is ”on”. If one heat pump has filled up its storage, the signal is transmitted to the next heat pump in the next house. There is a chain of n heat pumps in a row. Those n heat pumps share a slot of 3 kW in our system. This means we have four rows in total with n heat pumps in each row as it is shown in Figure 5.

If the signal is ”on”, the 12 kW power are not needed in the electrical grid and we have to switch on all four heat pump slots. In every heat pump slot, there is a control strategy based on the storage temperature of the house. The houses are numbered from 1 to n and when house i ($i \in 1...n$) has a full storage (the temperature rises above a certain temperature T_{max}), the on-signal is passed to house i+1 (if i+1=n+1, the next house is 1). The chosen storage temperature at which the signal is transmitted is at $T_{max} = 65°$C. The control procedure for each heat pump row is illustrated in Figure 6. If the on-signal is at a certain house i at the end of a time period $x \cdot T$, the same house i will get the on-signal at the time when the general signal switches to on again. The signal is moving around between the houses several times during the year. This ensures that every house gets a part of the generated electricity.

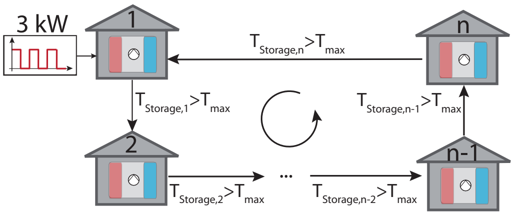

Figure 6: Control system for one heat pump row.

This will be done as long as it does not happen that in a time period of 15 minutes, all houses got an on-signal. If this happens, all houses are switched to "off" for another 15 minutes, because this means that all storages are completely full and just little amounts of energy can be stored. The excess electricity has to be fed into the grid which means in this situtation that it is fed into the medium or high-voltage grid. This is in contrast to the normal feed-in which is completely consumed in the low-voltage-grid.

RESULTS

For a broad analysis we chose to run several simulations for different numbers n of heat pumps. The number n varies between 2 and 12. The periods T are varied between four hours, one day and five days to determine which influence the length of the period has on the efficiency and on the reliability concerning the balancing of the electrical grid. For every n and every T, we chose different values for x to get a good insight how the system behaves with different shares of the on-signal. A higher x can be seen equivalent to a higher share of renewables in the grid.

The question we want to answer is to what extent the heat pumps can avoid the feed-in of the fuel cell into the grid in times they are forced to and how energy efficient this will be. These are two aspects which are very important in the evaluation of systems with a higher share of renewables.

Balancing energy

To determine to what extent the system is able to balance the electrical grid, we have to sum the runtimes of all considered heat pumps in one heat pump row. If the sum is equal to the total desired runtime of the heat pumps (displayed by the on-signal), we can obtain that it is possible to completely control the behaviour of the total plant in this case. As a mean to evaluate the balancing potential of the system, we use the balancing rate β which is defined in Equation 1.

$$\beta = \frac{\sum_n t_{r,HP}}{x \cdot t_{year}} \qquad (1)$$

Some of the resulting balancing rates are shown in Figure 7. The shown values for x are 10 %, 50 % and 90 % to see the differences between low (x = 10 %), medium (x = 50 %) and high (x = 90 %) sharings of renewables in the grid. We show only the behaviour of the total system for the time periods T of four hours and five days, because the balancing rates with T chosen to one day are very close to them calclulated for the case with four hours.

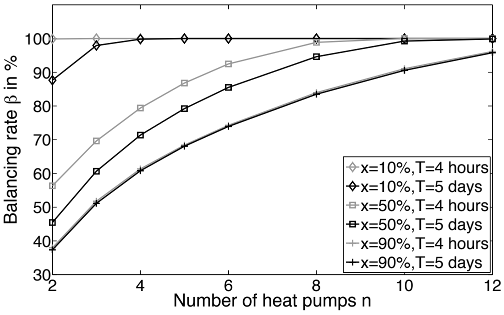

Figure 7: Balancing rates β for different configurations.

We can see that the balancing rates are increasing with the number of heat pumps which is obvious since with more heat pumps and their belonging storages we have a higher storage capacity. It is also clear that the balancing rates are higher for lower values of x. This means that the times in which the heat pumps should run are shorter and thus the storages are not loaded that much. The curves for T = 4 hours and T = 5 days are differing for a low and a medium value of x. The cases of T = 5 days deliver lower balancing rates in these cases. This means that the system cannot fill the storages any more because the period in which the heat pumps have to run are too long at a time. With a high value of x, we can obtain that the balancing rates for both time periods are very close to each other. This means that if x is that high, it does not matter how low the total period is in terms of the balancing rate.

If the value of x is low, with a number of four heat pumps a balancing rate of 100 % can be reached. For medium values of x, a number of ten to twelve heat pumps leads to a balancing rate which is 100 % or at least close to 100 %. For high values of x, balancing rates of 100 % cannot be reached by any of the investigated variants.

Energy efficiency

Besides the aspect of balancing the electrical grid, it is necessary to analyse the energy efficiency of the considered system. For this, we need a reference system. Both the reference system and the considered system in this paper are based on a gas supply, so that the amount of used gas is adequate to compare both systems. Our reference system consists of condensing boilers in every house with an assumed average efficiency of 95 % (Wolff et al., 2004) and a gas turbine with an electrical efficiency of 40 % (Lechner and Leume, 2010). Those two components are chosen because they are standard systems for heat generation and for keeping the electrical balance. Because we are analysing a system which should react fast to balance the electrical grid, a gas turbine seems to be the actual option to deliver this service to the grid. Other decentralized systems such as combined heat and power processes based on internal combustion engines could also be compared to this reference system.

Other factors such as grid or transformer losses are neglected in this examination. For a closer look on the efficiency, we use Equation 2 to calculate the theoretical savings of the investigated system compared to a reference system. Our system consists of the fuel cell, the heat pumps and the peak-load-boilers. The reference system includes a gas turbine and gas boilers in every house.

$$\xi = 1 - \frac{\frac{W_{el,FC,year}}{\eta_{el,FC}} + \sum_{4n} W_{gas,boiler}}{\frac{(1-x)\cdot W_{el,FC,year}}{\eta_{el,GT}} + (4 \cdot n + 1) \cdot W_{gas,ref}} \tag{2}$$

For the evaluation, it is necessary to consider the complete amount of gas that is needed in both cases. In the system analysed in this paper, the gas demand consists basically of the gas used by the fuel cell and the gas used by the peak-load-boilers in all houses equipped with heat pumps. For the reference system, the gas for the electricity needs (everytime the signal is ”off”, because this means that the electricity is needed) and the gas for all boilers which were needed in this case are considered. We have 4n+1 buildings in the system (one with the fuel cell and 4n heat pumps), so we have to consider 4n+1 boilers for the reference system.

If a certain system does not fulfil the requirements of the electrical grid as they are mentioned before, the surplus electrical energy has no real value and has to be fed in to a higher-voltage electrical grid and we cannot determine to what extent it can be used. Thus, this electrical energy is not considered in the energy balance except for the gas which is used to generate it.

The resulting energy savings are shown in Figure 8. Again, we chose low, medium and high values for x and the shortest and the longest analysed time period. In the case of a low value for x, we see a decreasing energy efficiency with an increasing number of heat pumps. This can be explained by the high value of the balancing rate for a low number of heat pumps. This means that a system with a low n can store more of the needed heat in its storages and an increase of n leads to the problem that more buildings have to be heated and the gas consumption for this is increasing because every house is getting only a little piece of the excess electrical energy. The difference between the case with a long time period and a short time period is very small.

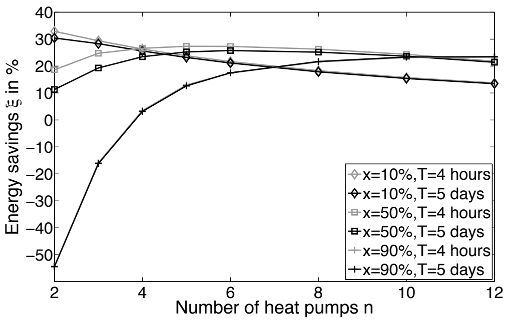

Figure 8: Energy savings compared to the reference system for different configurations.

For a medium value for x, the energy efficiency increases up to a number of heat pumps of six and decreases after this. This shows that the efficiency of the system is not the best if we can use the total electricity but in a situation when the balancing rate is between 85 % and 95 %. This means that we have to look at the trade-off between balancing the grid (which could be important in terms of security of energy supply) and the energy efficiency. The values for energy efficieny are always lower with the longer time period T. The higher the number of heat pumps is, the more both figures are approximating.

The energy savings in the case of the high value for x are below zero for systems with a low number of heat pumps. For two heat pumps in one row, the system needs about 50 % more gas than the reference system. This is caused by the high amount of electricity in these cases which is generated by the fuel cell, but which cannot be used by the total system. With an increasing number of heat pumps, the efficiency is also increasing. Again the results for both analysed time periods are nearly identical.

Other analysed scenarios

Additional to the aforementioned systems, we wanted to analyse some changes in the system and their influence on the basic results. To obtain an easily to interpret result, we conducted the parameter variations using a fixed number of heat pumps n. If it is not stated different, we chose the system with n = 3 as the standard system and analysed two cases: One with x = 10 % and one with x = 25 %. The case of n = 3 was chosen, because there is some potential to improve the balancing rates.As we saw before, the balancing rate in the ”standard” system was different for low and medium values for x. For the system with 3 heat pumps, x = 25 % is quite high, so we call this value in this section the high value.

As variations, we first analysed an increase of the storage capacity in each house with a heat pump from

1000 litres to 2500 litres. Afterwards, we took the standard system with a storage of 1000 litres and reduced the maximum temperature from 65 °C to 55 °C. As third variation, we analysed a combination of both. We increased the volume of the storage to 2500 litres and decreased the maximum temperature to 55 °C.

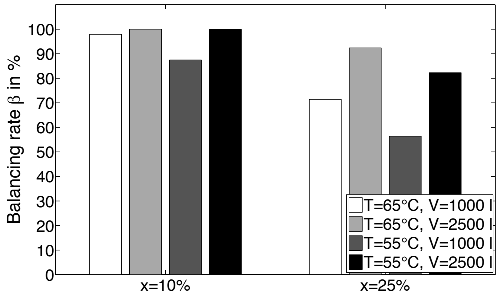

Figure 9: Balancing rates β for different configurations with a chosen number of heat pumps (n=3) and a certain time period (T = 5 days).

In Figure 9, we can see the resulting balancing rates for the different changes and in Figure 10, we can see the savings compared to the reference system for all analysed variants. The increase of the storage capacity leads as expected to a higher balancing rate in both cases. In the case with a higher x, we can see a much bigger rise because in the case with a lower x, the system was already close to a balancing rate of 100 % and the potential to get a higher balancing rate was limited. If we look at the energy savings, we can see that the rise of the balancing rate in the case of a lower x does not lead to a rise in energy savings. In the case of the higher x, the energy savings can be rised.

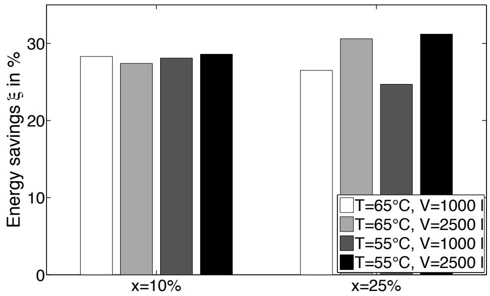

Figure 10: Energy savings compared to the reference system for different configurations with a chosen number of heat pumps (n=3) and a certain time period (T = 5 days).

The decrease of the storage temperature leads as expected to a lower balancing rate than in the standard case. This is due to a lower storage capacity which comes with a lower maximum temperature in the storage. The energy savings stay in the case of a lower x at a nearly constant level while they slightly fall for the case with a higher x. If both schemes (increasing of storage volume and decreasing maximum temperature) are combined, the balancing rate is 100 % for the lower x and is therefore equal to the one with only a bigger storage. In the case of a higher x, the balancing rate of the combined system is between the two system variations mentioned before, but it is higher than in the standard case. The energy savings are the highest in both variants of x.

These variations of parameters show that several parameters influence the ability of the system to balance the electrical grid and the energy efficiency. Especially if the balancing rate is low, varying the storage capacity can lead to higher values in terms of efficiency. Again, we can see that higher balancing rates do not automatically lead to higher efficiencies because the heat pumps run more often in bad operation points because of higher storage temperatures in average. This means that the price for a balancing rate of 100 % compared to a balancing rate of 95 % can be a falling energy efficiency. If the balancing rate is already close to 100 % in the standard system, changes in the shown system parameters have a lower influence.

CONCLUSION

This paper has shown that systems based on decentralized technologies for a supply of buildings can play a role in balancing the electrical grid. The presented system consists of a fuel cell with a high electrical efficiency and several heat pumps that are used to modulate the exported power. The total system can reach high balancing rates of up to 100 % depending on the number of heat pumps. Additionally, the gas consumption of this system is up to 33 % lower than in the reference system. This means that a considerable reduction is possible.

The system's efficiency can go down if a too low or a too high number of heat pumps is used. For every T and every x, there is not only one number of heat pumps which delivers good results, but several combinations are possible.

If the number of times when the heat pumps have to be switched on increases (represented by x), the number of houses equipped with heat pumps should be increased too to get a higher efficiency. This means that the system can be designed to grow with the integration of a higher share of renewables in the electrical grid. The number of heat pumps (participating households) could be increased progressively.

The economical feasibility will depend on the compensation which the households get if they participate in a load management for the electrical grid. The development of this market seems to be uncertain so that we cannot determine if the system presented in this paper could be economically feasible. This will also depend on the costs for thermal storages and the costs for alternative storage systems for electrical energy. We have to ensure that all households can participate best at the load management which means that we have to guarantee equal runtimes of the heat pumps for every building. The economical potential could be increased by using the surplus heat or the surplus electrical energy in summer for cooling to get the maximum utilization of the energy input. This will be investigated in further work.

The heat pumps were simulated separately from the fuel cell because their only interconnection would be the electrical grid which is not represented physically in our model. Because of this, the same methodology could be used to use the heat pumps to directly consume energy from the grid if it is necessary because of production peaks, e.g. due to photovoltaics.

In total, it can be determined, that this system is appropriate to be used for load management in low-voltage grids. Further detailed analyses will follow. These analyses will include the possibility of a usage of the building mass as a storage. Additionally, a detailed analysis of the electrical grid will follow. This is also concerning the development of a method to generate the "on/off-profiles" which could be extended to a method where different steps are available not only the cases of "on" and "off". Also the analysis of real photovoltaics and wind feed-in situations will be included. Different house types and user behaviour and their influence on the efficiency of those systems will be also analysed in further work.

NOMENCLATURE

T	time period for heat pump signal
x	share for on-signal in T
n	number of heat pumps in every row
i	index of actual heat pump
T_{max}	maximum temperature of heat storage
ξ	energy savings
$W_{el,FC,year}$	electrical work generated by the fuel cell for a total year
$\eta_{el,FC}$	electrical efficiency of the fuel cell
$\eta_{el,GT}$	electrical efficiency of the gas turbine
$W_{gas,boiler}$	gas demand for every boiler
$W_{gas,ref}$	gas demand of the boiler in reference system
$t_{r,HP}$	runtime of each heat pump
t_{year}	time of the whole year

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