Renewable-Energy-Driven Heat Pumps for Districts to Reduce Primary Energy Demand

Elisabeth Schneider[1], Tobias Ohrdes[1], Ann-Kathrin Fries[2], Michael Knoop[3], Oliver Bast[3], Joachim Behnisch[4]

[1] Institute for Solar Energy Research Hamelin, Emmerthal

[2] Institute of Electrical Power Engineering and Energy Systems TU Clausthal, Clausthal

[3] STIEBEL ELTRON GmbH & CO. KG, Holzminden

[4] Energieservice Westfalen Weser GmbH, Kirchlengern

Abstract

Renewably driven heat pumps (HP) have considerable potential for primary energy savings in districts. Using measurement data of an existing district, this article shows the potential of a renewable heat supply using heat pumps. A simulation model for heat pump districts is presented, which has been validated by measured data. Using this model, heat pump control strategies in combination with different supply concepts are developed and examined by simulation. The results show that a renewable coverage of up to 80% can be achieved by using suitable heat pump operation strategies in combination with local photovoltaic (PV) and wind power (WP) as well as battery storages with 6 kWh capacity per building. It is also possible to increase the share of renewable energy to a complete satisfaction of demand. For the scenario considered, this would require a four times higher renewable energy production than the annual demand in the district and a battery capacity of 30 kWh per household.

Keywords: Heat pump, Control strategies, Renewable Energy Prediction, Sector Coupling, District.

1. Introduction

The renewable energy (RE) supply of buildings and districts is an important condition for reducing CO2 emissions. While 45% of electricity in Germany (Fraunhofer ISE, 2019) is generated from renewable energies, the heating sector lags far behind. In private households, 83% of the final energy is used for space heating and domestic hot water (AG Energiebilanzen, 2019a) produced with a renewable heat share of currently only 14% (AG Energiebilanzen, 2019b).

Heat pumps are considered as key technology for the energy transition in the heating sector, since they offer a large potential for reducing CO2 emissions. This potential can be exploited if the electricity for heat pumps is simultaneously covered by renewable energies from wind power and photovoltaic systems. In order to bring supply and demand into line and thus relieve the strain on electrical grids, coordinated operation of heat pumps in districts could be beneficial. Within the framework of the research project "Wind-Solar-Heat Pump Urban District", a model is being developed that calculates the power and heat requirements in the district on a detailed building level and determines the power flows in the electrical distribution network dynamically over the course of the year. The model enables the evaluation of operating strategies for heat pumps with regard to relieving the load on the electrical distribution networks and reducing the primary energy demand in the district.

doi:10.18086/eurosun.2020.02.10 Available at http://proceedings.ises.org

2. Measurements in real districts

Within the framework of the research project, measurements of electricity and heat consumption are carried out in two districts. One of these districts is the solar district at Ohrberg near Hamelin in Lower Saxony (Germany). It was built around the year 2000 and contains 70 low-energy single-family houses with a specific heat demand of about 45-50 kWh/m²/a (Toelle et al., 2002). All buildings are equipped with water-water-heat pumps connected to a cold local heating network. The cold local heating network is a special feature of this district: it provides an approximately constant source temperature of 12 °C for the heat pumps throughout the year.

In order to make detailed statements about the power consumption of heat pumps and households, more than half of all buildings were equipped with measuring instruments. The electrical power consumption of heat pumps as well as all household loads of these building are recorded in intervals of 10 seconds. In addition, local photovoltaic systems, the local network transformer and the cold local heating network are equipped with measuring instruments. Weather data such as ambient temperature and solar irradiation as well as data from local wind power plants complete the entire energy monitoring of the district.

3. District model

In order to analyze heat pump districts and determine optimization potentials, a simulation model for heat and electricity in the district was developed within the project. The model enables all important components of the building energy supply to be described with their dynamic behavior for each building separately. The building models are integrated into an electrical distribution network at district level. The district simulation is carried out in steps of one minute for any period of time. For this purpose, measured weather data, measured household load profiles and domestic hot water (DHW) profiles generated with “DHWcalc” (Jordan and Vajen, 2017) are used as input. A constant heat pump source temperature of 12 °C is assumed to represent the heating network. No thermal or hydraulic model for the heating network is used. The simulation is used to determine heat load profiles of the individual buildings and the electrical load on the local network transformer. Under dynamic conditions, control strategies at building and district level can be investigated and evaluated for different district structures and building energy systems.

3.1. Building Model

Simplified component models are used to represent the individual buildings and their respective supply system. The models are based on or derived from scientifically recognized models or validated using the TRNSYS simulation program. The individual component models are briefly presented below:

The thermal building model is represented by a node model consisting of RC elements. For this purpose, the two-node building model according to Koene et al. (2014) was extended by two additional nodes for the heating system. The building model is based on a few parameters such as thermal building capacity, thermal resistances of the building envelope and for ventilation and heat gains, which are either determined from building physics data or determined from measurement data using an automated procedure (Schneider et al., 2019).

The thermal model for storage tanks for DHW and heating system were also created based on a few RC elements and validated using TRNSYS type 340 (Drück, 2006). As a reasonable compromise between model accuracy and computational effort, we model the storage tank with four nodes. In addition to direct loading and unloading, it also allows the use of a simplified modeled internal heat exchanger.

The heat pump is modeled following the TRNSYS type 401. The model is based on biquadratic polynomials, which represent the steady-state operating conditions of the heat pump. In addition cycling losses due to heating-up and cooling down processes are modeled via PT1 elements. For air-source heat pumps, de-icing losses are also taken into account (Wetter and Afjei, 1996). The model can be used to represent both fixed-speed and inverter-controlled heat pumps.

For modeling the PV system, the incident angle reflection losses of the module are considered using the approach of the American Society of Heating, Refrigeration and Air Conditioning (1977). Considering the PV module temperature according to G. Tamizhmani et al. (2003), the DC power is calculated. The thermal inertia of the modules is taken into account using a PT1 element. The conversion efficiency of the PV inverter is calculated using the "PerMod" model of HTW Berlin (Weniger et al., 2019).

The battery storage is also modeled using the “PerMod" model from HTW-Berlin (Weniger et al., 2019). This takes into account conversion losses of the power electronics, standby losses, battery losses and static and dynamic control deviations.

The power of the wind turbines is calculated using the characteristics of a 2 kW generator with a hub height of about 100 m.

The models were validated using measurement data from the Ohrberg district.

3.2. Energy Management

The operation of all components is controlled in an energy management module. This enables the implementation of control strategies (CS) at building and district level. The following operating strategies are examined:

1. Decentralized heat demand-driven control strategy (CS 1)

The heat pump starts heating as soon as the temperature in the DHW storage or heating tank falls below the defined lower temperature limit. It stops heating when the upper temperature limit is reached. The heating storage tank heats the building to a setpoint temperature which is also specified. If a battery storage exists, it operates with regard to the electrical house connection point in order to minimize the load transferred to or from the grid. If wind energy is considered for RE production, it is also be included in the battery control strategy.

2. Decentralized control strategy optimized for RE coverage based on forecasts (CS 2)

The following forecasts are generated:

- PV and wind energy forecasts based on ideal weather forecasts,
- ideal forecasts of electrical household loads,
- ideal forecasts of the DHW and of the building heating energy demand, assumed as basis for the prediction of the storage temperatures and the electrical demand of the heat pump.

Based on these forecasts, the temperature limits of the thermal storages as well as the room set temperature of the building are controlled flexibly: First of all, the non-shiftable electrical household loads are subtracted from the renewable energy production. If, as shown in Figure 1, no or insufficient RE is available for heat supply, but a sufficient amount of RE is expected in the near future, the upper and lower temperature limits (T_U and T_L) of the thermal storages are shifted downwards ($T_{U\ new}$ and $T_{L\ new}$), as well as the setpoint room temperature of the building. Because even lower temperature values are permitted for a short time, the system avoids the use of grid power for heating and uses the predicted RE yield for powering the heat pump. The optimal temperature shift was determined by previous simulations in order to maximize renewable coverage. The temperature reduction was chosen in such a way that no significant restrictions in comfort occur for the building temperature or the DHW.

If a surplus of RE is available, as shown in Figure 2, shortly before the end of the predicted surplus, the temperature limits of the storage tanks and the building temperature are shifted upwards ($T_{U\ new}$ and $T_{L\ new}$), so that the surplus of RE energy is stored as heat. Outside the heating period, the heating storage tank is not charged, therefore only the DHW storage tank is available.

If a battery storage exists, it operates similar to CS 1, in order to minimize the load transfer at the house connection point.

3. Central control strategy optimized for RE coverage based on forecasts (CS 3)

The central RE consumption-optimized control strategy at district level is similar to the decentralized RE consumption-optimized operation strategy at building level and uses the same forecasts, with the difference that the energy balances are considered at district level and not at building level. If there is currently no or too little renewable energy available for heat supply and if the forecast renewable energy production is sufficient to cover the entire district demand, the temperature limits of the thermal storages and buildings are reduced here as well. If sufficient renewable energy generation is predicted, the heat pumps of the buildings with the currently lowest temperatures are successively put into operation according to a calculated demand ranking, until the total capacity of the heat pumps almost corresponds to the available renewable energy generation.

All battery storages operate with regard to the local grid transformer, in order to minimize the load transfer for the whole district. All decentralized existing batteries are synchronously charged or discharged. In terms of energy balance, this is identical to a large central district battery storage.

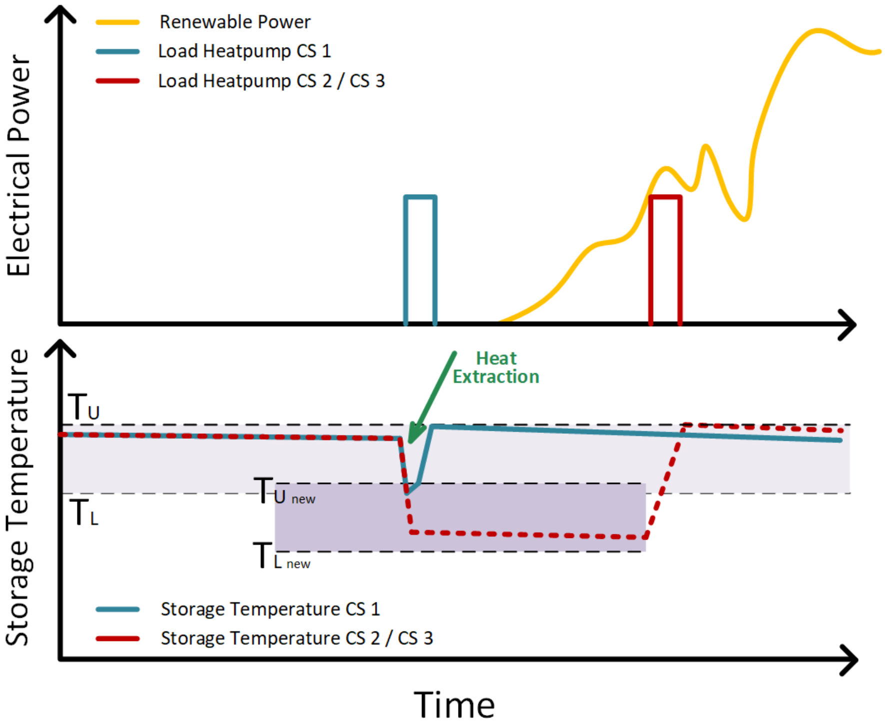

Figure 1: Schematic illustration of reducing the storage temperature limits in CS 2 and CS 3 in case of soon expected EE-production

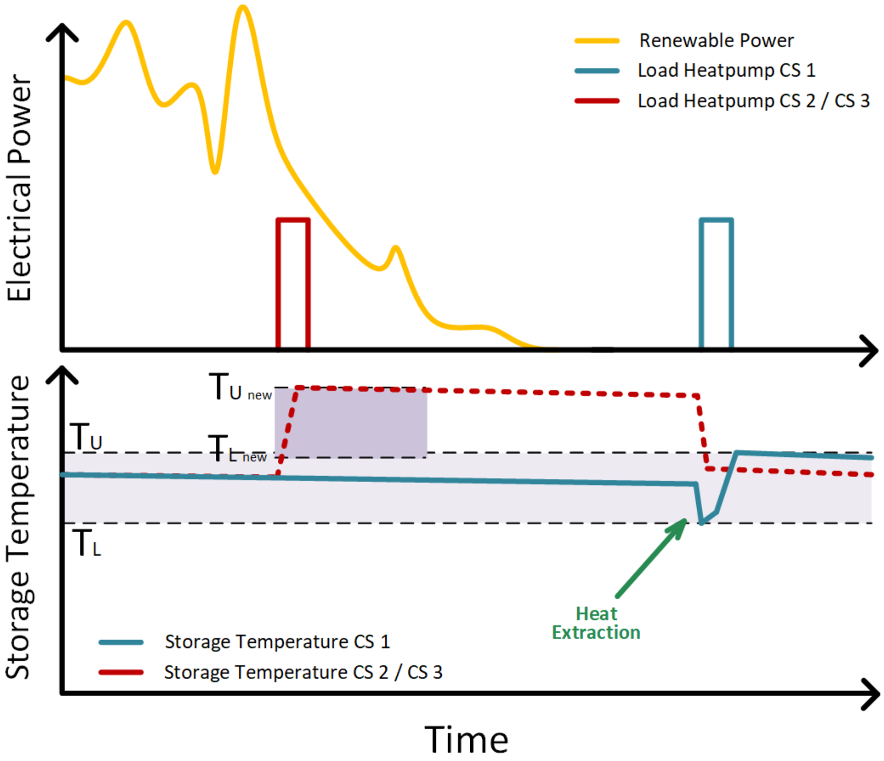

Figure 2: Schematic illustration of increasing the storage temperature limits in CS 2 and CS 3 in case of an energy surplus

4. Scenarios for a renewable district supply

Based on the district model, different supply scenarios are examined. First of all, the supply of RE is analyzed for the monitored Ohrberg settlement. With a heat demand controlled HP control strategy (CS 1) without battery storage, the generation power of PV and wind energy is varied. Figure 3 shows the RE coverage rates for different nominal powers of PV and wind power plants.

The graph shows that with a RE production to energy consumption ratio of 1:1 (energy demand coverage with locally produced renewable energy is 100% in the annual balance), a maximum RE coverage of 32% can be achieved with PV supply alone. If only wind energy is used instead of PV, a maximum degree of coverage of 50% can be achieved. By combining both energy sources, a degree of coverage of up to 56% is possible. The maximum RE coverage can be obtained with a PV-to-wind nominal power between 1:1 and 1:2. The RE coverage rate can be further increased by increasing the RE production/consumption ratio.

Using the developed district model, the potentials of building energy systems and their energy management for RE supply can be evaluated. The basis for the following results is again the district structure as it is found in the district at Ohrberg. In six scenarios, the building energy technology is successively supplemented with additional components, such as energy management for heat pump or battery storage. For the installation of renewable energies it is assumed that the available roof areas of the buildings are covered either with 4.2 kWp PV systems each or with 2.1 kWp PV systems, if combined with 1.4 kW wind energy. The capacities are chosen in such a way that approximately as much energy is generated by RE per year as is consumed in all buildings. The dimensions of the individual components are in the range of those normally found in households.

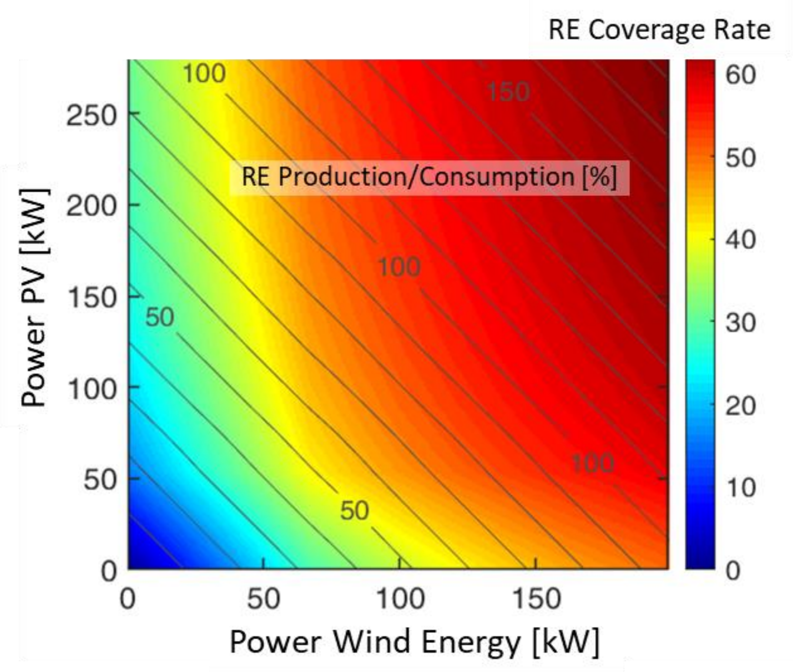

Figure 3: RE coverage depending on nominal PV and wind power

The results of the following six scenarios are shown in Figure 4. It should be noted that the renewable coverage refers only to the electrical energy. A total energy consideration, which also includes the regenerative environmental energy used by the heat pumps, would result in an even slightly higher share of renewable coverage.

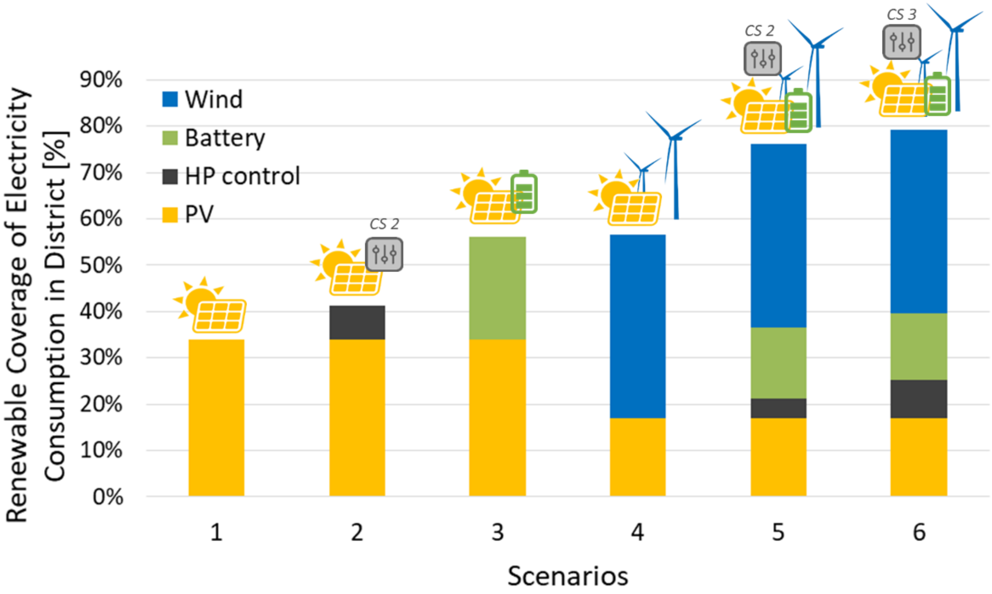

Figure 4: Renewable coverage of electricity consumption in the district for various scenarios with a ratio of renewable energy production to consumption of approx. 1

1. In scenario 1, each building is equipped with a PV system with a size of 4.2 kWp. The HPs are operating on a heat demand basis (CS 1). This results in a renewable coverage of 33% at district level.
2. In scenario 2, the HPs are operating RE consumption-optimized, taking into account the PV systems and based on forecasts at building level (CS 2). This increases the renewable share of coverage to 41%.
3. In scenario 3, the PV systems are each extended by a 6.3 kWh battery storage. Here, the heat demand-driven operation strategy (CS 1) is applied again. The renewable share of coverage is increased to 56%.
4. In Scenario 4, using the heat demand-based operation strategy (CS 1), 2.1 kWp PV and 1.4 kW wind energy are assumed for each building. This already achieves a coverage of 57% without using a battery storage.
5. In scenario 5 all extensions of the previous scenarios are combined. Based on forecasts at building level, the RE consumption-optimized operation strategy (CS 2) is applied. In this way, local renewable coverage rates of 76 % are possible.
6. Scenario 6 is identical to scenario 5 except for the operation strategy, which uses the renewable energy consumption-optimized operation strategy at district level based on forecasts (CS 3). This way, renewable coverage shares of almost 80% are possible.

The results show that the coverage rate of a PV system can be increased by 24% just by using a RE consumption-optimized HP operation strategy, i.e. by shifting the HP operating times. Furthermore, the combination of PV (2.1 kWp) and wind energy (1.4 kW) without battery storage achieves approximately identical RE coverage rates as the PV system (4.2 kWp) in combination with a battery storage (6.3 kWh). This is due to the high simultaneity between wind energy and heat pump utilization, especially in the winter months. Furthermore, it also shows that PV and wind energy complement each other well for the heating requirements of residential buildings during the course of the year. Moreover, it can be seen that a centralized district control is preferable to a decentralized approach, since it allows additional balancing of power between different buildings and through load prioritization a higher amount of RE can be used.

The following section examines which measures are necessary to achieve almost 100% renewable energy supply in the district with scenario 6. For this purpose, the installed PV and wind energy power capacities are scaled in simulations, so that in addition to the 1:1 ratio of RE generation to consumption, ratios of 2:1 and 4:1 are also considered. Additionally, the battery storage sizes are varied. Figure 5 shows the RE coverage rates achieved for the different parameter combinations.

The results show that 100% RE coverage is possible for the scenario considered here with a generation/consumption ratio of four and a battery storage capacity of 30 kWh/building. A battery capacity of 30 kWh per building is quite conceivable if it is assumed that in the future, for example, batteries from electric vehicles will also be included in energy management. With double renewable energy generation and the same battery size, a renewable energy coverage of 97% is already achieved, and with the reference renewable energy generation a renewable energy coverage of 85%. Thus, a significant increase in RE generation capacity would lead to much higher investment cost but relatively little gain in RE coverage.

In general, it should be noted that the limitation of RE coverage is caused by individual low-wind phases in winter, when there is a high demand for heating energy and little PV yield is generated anyway. The achievable annual RE coverage is therefore particularly dependent on the winter weather. Consequently, the presented results are to be evaluated taking into account the specific weather data used.

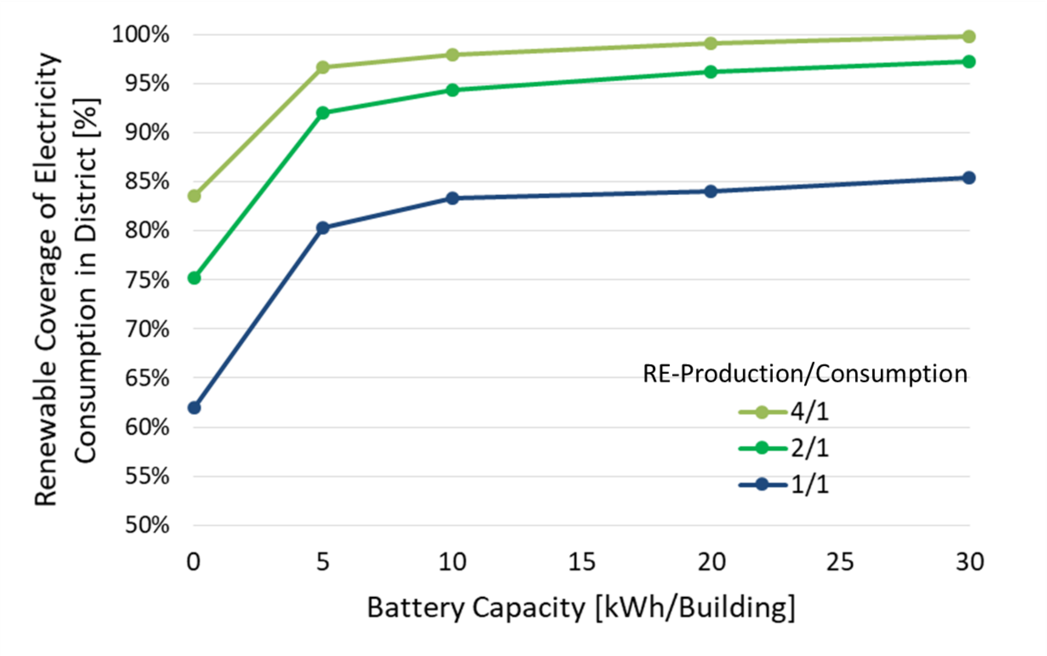

Figure 5: Renewable coverage in the district for supply scenarios with scaled RE generation and different battery storage capacities

5. Summary and outlook

A district model was developed that can simulate the electricity and heat demand over the course of a year. This offers the possibility to evaluate different supply concepts and operating strategies in districts. At first, supply scenarios were considered whose energy production is equivalent to the annual demand in the district. The results show that for an existing PV system an increase of the PV coverage in the building of 24% is possible, just by the use of low-investment measures such as energy management with intelligent heat pump control and weather forecasting. It is also shown that control strategies on district level are more efficient than on building level. For the considered scenario with local PV and wind power and battery storages with 6 kWh per building a central control strategy leads to an increase of 4% of RE coverage in district. Altogether with this RE supply quantity, RE coverage rates up to 80% can be reached in district.

An increase in the degree of coverage up to 95% is possible by doubling the renewable energy production and the battery capacity. For a full renewable supply, a quadrupling of the renewable energy generation and a 30 kWh battery capacity per building are necessary. A reduction in the required renewable energy production capacity would be conceivable if other types of consumers were included in the district balance, e.g. from trade and industry, that have different electrical load profiles and can also provide waste heat for heating residential buildings.

Furthermore, the described forecast-based HP operation strategies can be optimized by means of mathematical optimization methods and with regard to further objective functions. Besides the renewable coverage, objective criterions such as primary energy demand, CO2 emissions or fluctuating exchange prices of electricity are also of interest.

6. Acknowledgement

The research work on which this publication is based was carried out in the frame of the joint project "Wind-Solar-Heat Pump Urban District”, with funds of the Federal Ministry for Economic Affairs and Energy under the reference number 03ET1444A based on a resolution of the German Federal Parliament and supported by the Lower Saxony Ministry of Science and Culture. The authors are grateful for the support. The responsibility for the content of this publication lies exclusively with the authors.

7. References

AG Energiebilanzen e.V., 2019 a. Anwendungsbilanzen für die Endenergiesektoren in Deutschland in den Jahren 2013 bis 2017. Berlin.

AG Energiebilanzen e.V., 2019 b. Auswertungstabellen zur Energiebilanz Deutschland. Berlin.

American Society of Heating Refrigeration and Air Conditioning, 1977. ASHRAE standard 93-77. New York.

Drück, H., 2006. MULTIPORT Store - Model for TRNSYS. Institut für Thermodynamik und Wärmetechnik (ITW) Universität Stuttgart.

Fraunhofer ISE. Energy Charts. [Online]. Available: https://energy-charts.de. [Accessed: 26-Nov-2019].

Jordan, U., Vajen, K., 2017. DHWcalc. Universität Kassel, Institut für Thermische Energietechnik, Kassel.

Koene, F.G.H., Bakker, L.G., Lanceta, D., Narmsara, S., 2014. Simplified Building Model of District. BauSIM 2014, Aachen.

Schneider, E., Littwin, M., Knoop, M., Pärisch, P., Kastner, O., Ohrdes, T, 2019. Entwicklung und messwertbasierte Parametrierung eines vereinfachten Gebäudemodells für die Quartiersmodellierung. Symposium Solarthermie und innovative Wärmesysteme 2019, Bad Staffelstein.

Tamizhmani, G., Ji, L., Tang, Y., Petacci, L., Osterwald, C., 2003. Photovoltaic Module Thermal / Wind Performance : Long -Term Monitoring and Model Development For Energy Rating. NCPV Sol. Progr. Rev. Meet., pp. 936–939.

Toelle, L., Otto J., Christoffers, D. D., 2002. Qualitätssicherung mit Informations- und Beratungskampagne bei der Realisierung einer Solarsiedlung. Emmerthal.

Weniger, J., Tjaden, T., Orth, N., Maier, S., 2019. Performance Simulation Model for PV-Battery Systems (PerMod) [Online]. Available: https://pvspeicher.htw-berlin.de/permod/. [Accessed: 08-Nov-2019].

Wetter, M., Afjei, T., 1996. TRNSYS Type – Compressor heat pump including frost and cycle losses, Version 1.1. Zentralschweizerisches Technikum Luzern.