Smart Urban Energy Concept: Integration of Heat Pumps, PV, Cogeneration, and District Heating in existing Multi-Family Buildings

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Abstract

An innovative urban energy concept for a German district with five existing multi-family buildings integrates photovoltaics, heat pumps, and cogeneration units in a district heating grid for an energy-efficient and economic heat and electricity supply. Simulation results show the synergies of a smart integration of proven technologies: by means of optimized component dimensioning, a suitable hydraulic design and smart control strategies, the CO_2 emissions can be reduced by 52 %. At the same time, the district concept is economically viable showing a positive annual turnover.

The energy system will be implemented in 2020, followed by a scientific monitoring and evaluation of the performance. If the monitoring data confirm the promising simulation results, the energy concept can serve as a model for energy-efficient and economic renovation of similar districts.

Keywords: *heat pumps, smart grid, district heating, energy management, CO2 reduction,*

1. Introduction and motivation

The energetic renovation of existing multi-family buildings is a central challenge for decarbonizing the building sector. Heat pumps are a promising renewable heating technology with low CO_2 emissions if powered by renewable electricity. However, the implementation in multi-family houses faces technical (temperature levels, availability of heat sources, renewable power supply) and economic challenges.

An innovative urban energy concept is developed, implemented and monitored for a cluster of five multi-family houses within the project “Smart District Karlsruhe-Durlach”. The five buildings were constructed in the 1960s and comprise 175 apartments and a total heated floor area of 11.603 m². The buildings have already been insulated and renovated in 1995, and thus reach a relatively low specific heating demand of 53 kWh/m²/y. The heat demand for space heating and hot water is currently covered by gas boilers, while electricity is supplied by the power grid, resulting in a large CO_2 footprint.

Figure 1: Photo of the building (left, © Stefan Hess, INATECH) and the district (right, © Google Earth, Map data: Google, GeoBasis-DE/BKG)

The central objectives of the new energy supply concept are:

1) Reduction of CO_2 emissions by 50 %
2) Demonstrate the application of heat pump technologies in existing multi-family houses
3) Smart integration of proven technologies, connected by a central energy management system for optimized

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operation

4) Implement an energy efficient and economically viable concept, which allows for scaling and transfer to similar districts

This paper details the smart urban energy concept, which will be implemented in Karlsruhe-Durlach, with a focus on the energy management system and preliminary simulation results.

2. Smart integration of PV, Heat pumps and CHP

A multitude of different supply concepts and component dimensions were simulated with a specifically developed simulation tool. The optimization model varied the topology (i.e. the integration points of heat pumps and CHP, and the size of the district heating network) and the components dimensions (installed power of PV, HP, CHP, boiler and heat storages) within the given boundary conditions. The underlying optimization objectives were:

- Minimize CO_2 emissions from gas and electricity import, assuming CO_2 emission factors for electricity and for natural gas. CO_2 emissions are minimized by reducing the imports of natural gas and electricity and by increasing the export of electricity.
- Maximize annual earnings before interest and taxes (EBIT) for the contractor considering costs for investment, maintenance, gas and electricity imports and exports. The internal cost structure and the current German regulative situation with EEG tariffs and CHP and tenant bonuses were considered. EBIT is maximized by low investment and low operational costs.

Next to simulation results and the corresponding energy balance, the German regulatory boundary conditions (EEG, KWKG, Mieterstrommodell, BMWi 2017) and local restrictions (crossing of street, limited space in basements, design of new heating plant) were considered.

Based on these considerations, the final energy concept shown in Figure 2 will be realized and implemented until the end of 2020:

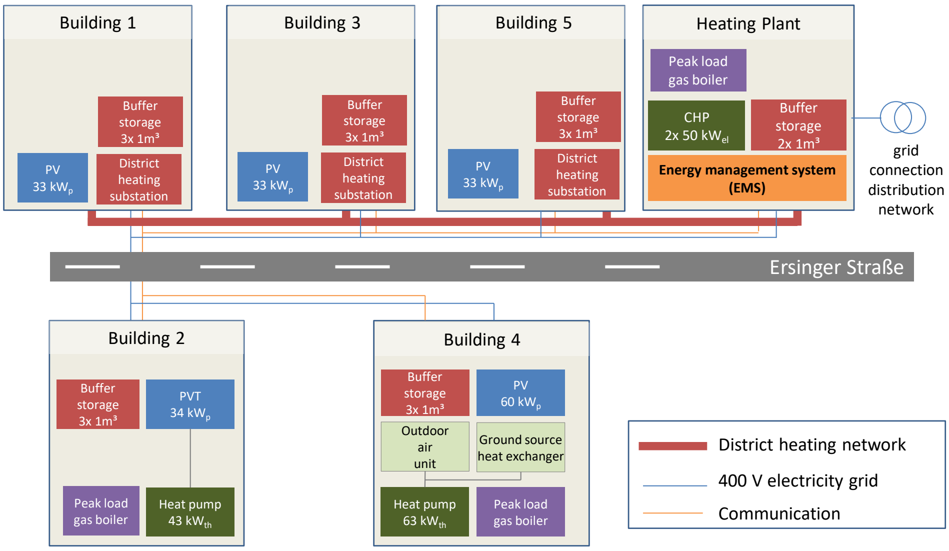

Figure 2: Energy supply system for the smart energy district Karslruhe-Durlach

PV modules are installed on all five buildings with a total power of 194 kW_p. Optimization results for the energy concept showed, that large PV capacities are beneficial under both economic and energy efficiency considerations due to low levelized costs of electricity and low carbon intensity. However, owing to legislative regulations, the installed power is limited to 100 kW_p per year. The PV arrays will therefore be installed in two stages.

Two decentral heat pumps supply heat to building 2 and 4 with a thermal power of 43kW_{th} and 63 kW_{th}. The heat pumps use innovative low temperature sources, which specifically address the challenge of limited heat sources in urban areas (Hess et al., 2019). Heat pump 1 in building 2 is coupled to hybrid photovoltaic/thermal PVT collectors with a total area of 200 m². Uncovered PVT collectors with enhanced heat transfer of ambient energy through a finned heat exchanger at the rear side (Leibfried et al., 2019) are used as the sole source for the heat pump with a thermal power of 43 kW_{th}. Heat pump 2 in building 4 uses a dual heat source with intelligent control and hydraulics.

Compared to a single-source heat pump, only 50 % of ground source heat exchanger is required. The remaining thermal power is supplied by an air-to-water heat exchanger. It is expected to achieve a seasonal performance factor similar to a ground-source heat pump while investment costs are in the range of an air-source heat pump (Günther and Obermann, 2019). Low supply temperatures on the heating distribution side are achieved by hydronic balanced heating systems, a selected exchange of 10 % of all radiators in the apartments (Lämmle et al., 2019), and an ultrafiltration unit in the drinking water circulation which filters Legionellae mechanically.

Three buildings are connected to a district heating network, which is powered by a heating plant outside of building 5. Two combined heat and power unit (CHP) fueled by natural gas CHP units, each with a power of 50 kW_{el}/86 kW_{th}, supply heat to the district heating network and generate electricity for the district and heat pumps. These CHP units will also be commissioned in two stages owing to more beneficial feed-in-tariffs for smaller CHP plants in Germany. A new heating plant will be designed and constructed for this purposes, as the space is the basement was neither sufficient for a central solution with the heating plant integrated in the basement, nor a decentral solution with distributed CHPs. A two pipe district heating network will distribute the heat from the heating plant to the substations in each building.

All heat generator units (heat pumps and CHPs) have peak load gas boilers as auxiliary heating backup. Buffer storages are included in all buildings and in the heating plant to allow for a flexible operation of CHP and heat pumps. On the electrical side, the heating plant is equipped with a transformation station to benefit from lower import and export prices for electricity from the grid.

3. Energy management system

The new energy concept intelligently combines proven technologies to achieve energy-efficiency, a low CO_2 footprint and an economic business case for the energy contractor. This is also achieved by the smart operation of the heat pump and the CHP with the objective to optimize energy-efficiency and economics.

A local electricity grid connects all five buildings for this purpose. Thus, electricity from PV and CHP can be utilized locally by the heat pumps for power-to-heat applications. Moreover, the PV modules also supply tenants and households with locally generated electricity within the so-called “Mieterstrommodell”. Within this legislative framework, tenants can benefit from a local PV plant by lower electricity tariffs while the operator receives a small bonus per kWh of PV electricity sold to the households. However, the “Mieterstrommodell” is only applicable to PV and not to CHPs and all tenants can decide freely whether to participate or not.

Nonetheless, the local electricity grid enables an enhanced energy management. The target for the optimization is the maximization of self-consumption and self-sufficiency and thus economic profitability. For this purpose both cogeneration units in the heating plant and both heat pumps are connected to the central energy management system. Depending on the generated PV power and heat and power demand in the households, the energy management (Figure 3) system requests the operation of CHP or heat pump:

- The CHP units preferably operate in periods of high local electricity demand, as sum of electricity demand of households and heat pumps minus the PV power.
- The heat pumps preferably operate in periods of excess electricity, as sum of electricity from PV and CHP minus the electricity demand of households. For further flexibility, the heat pumps can be operated in discrete power stages with optional heating rod operation.

Hence, the energy management optimizes the operation of heat pumps and CHP for an optimized utilization of the intermittent generation of PV electricity, which ultimately leads to a maximized self-consumption and self-sufficiency and thus to an improved economic profitability and lower CO_2 footprint.

Next to rule-based heuristic control strategies, a more sophisticated model predictive control (MPC) approach will be developed, implemented and tested. The MPC approach considers weather and PV forecast, the current states of charge of the thermal storages, and models future heat and power demand with a neural-network trained demand prediction model. It is expected that the sophisticated MPC approach further optimizes self-consumption and self-sufficiency.

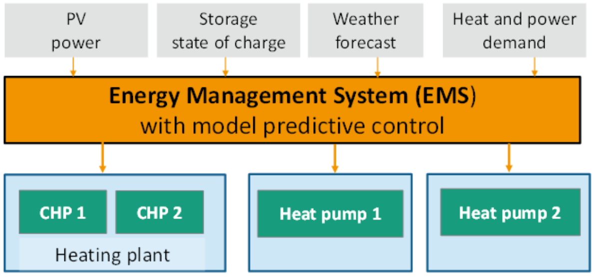

Figure 3: Functional structure of the energy management system with model predictive control strategies

Additionally, the energy management system integrates the following functions:

- Management level: monitoring, data storage, reporting, evaluation of performance
- Automatization level: control of heating plant and the district heating network
- Fault detection and diagnostics: implementation and testing of algorithms based on artificial intelligence

Thus, the smart integration of the basic technologies via the energy management system allows for an efficient and economic operation by optimizing self-consumption and self-sufficiency of PV and CHP electricity.

4. Simulated performance of the smart district

The energetic, economic and ecologic performance of the district was simulated with a specifically developed simulation tool for designing energy concepts for buildings and districts with a focus on energy management and integration of heat pumps in district heating networks.

Figure 4 illustrates the annual energy balance for the employed technologies and the energy flows between each component.

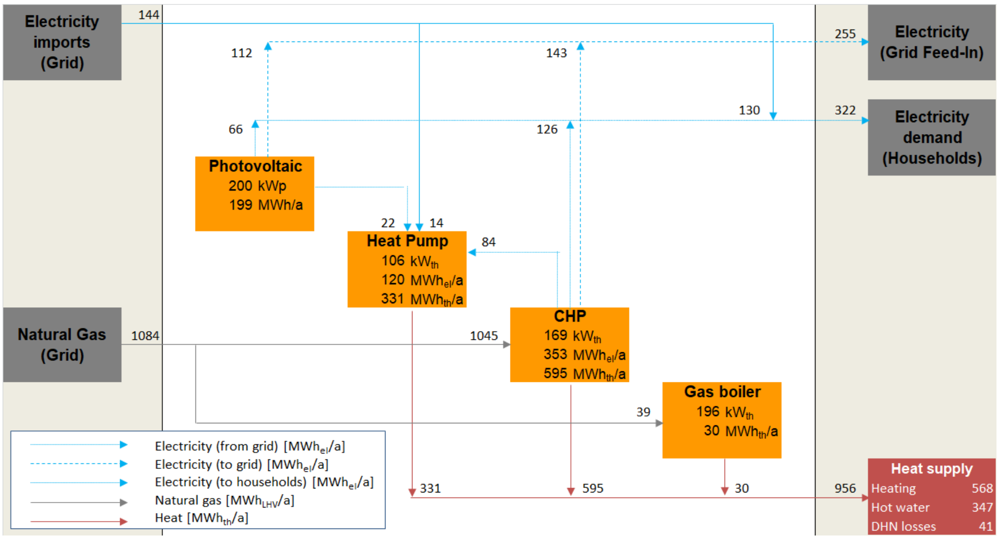

Figure 4: Annual energy flows of the smart energy district.
The simulation with the aforementioned components and topography yields the following key performance indicators:

The energy balance indicates an electrical self-sufficiency of the district of 67 %, i.e. two thirds of the electricity demand of households and the heat pump is generated locally by PV and the CHP. The heat pumps even achieve a self-sufficiency rate of 88 %. With regards to self-consumption, 44 % of the PV electricity and 59 % of the CHP electricity is consumed within the district.

Using German CO_2 emission factors for natural gas (227 g_{CO2eq}/kWh) and for electricity imports and exports (403 g_{CO2eq}/kWh, estimated electricity mix of 2020, Fritsche and Greß (2019)), the total CO_2 footprint is reduced by 52 % compared to the previous energy concept with grid electricity and decentral heat from gas boilers. Thereof, the heat supply is decarbonized by the heat pumps, which utilize ambient low temperature heat from air, sun, and ground, and low-carbon electricity from PV and CHP. The electricity generated from both PV and CHP achieves a significantly lower CO_2 intensity compared to electricity from the grid. Hence, PV and CHP yield a reduction of the CO_2 intensity for the electricity supply of the district.

With regards to the economic performance, the evaluation of investment and operation costs shows that the energy system achieves a similar economic performance as the current energy system. This allows for a profitable business case for the contractor and similar or even lower costs of energy for the tenants.

5. Conclusion and outlook

The energetic renovation of existing multi-family buildings is a central challenge for decarbonizing the building sector. The presented energy concept combines PV, heat pumps and cogeneration units for an energy-efficient supply of heat and electricity to a district with existing multi-family houses. The simulation results illustrate the synergies of integrating PV, HP and CHP in district heating grids: the smart combination of all three technologies allows a good balance between high economic profitability, energy efficiency and a low CO_2-footprint.

This is due to an optimized sizing of components, specific hydraulic design and a smart control strategy. The energy management system preferably operates the heat pump with excess PV or CHP electricity, and operates the CHP in periods with a high electricity demand. Thus, electrical self-sufficiency and self-consumption are improved and grid imports are reduced.

In 2020, the presented energy concept will be implemented in the district, followed by a period of optimization of operation, where the model predictive control strategies will be implemented and tests. Moreover, the performance of the buildings and the overall district will be monitored. If the promising simulation results can be verified by field tests, the energy concept can serve as a model for the energetic renovation of other districts.

6. Acknowledgments

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