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Simulation-based analysis of the effects of sector coupling and operational optimisation on the district heating and electricity grid

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Abstract. The role of district heating grids and power-to-heat technologies is crucial for improving energy efficiency and reducing greenhouse gas emissions in urban environments. The analysis focuses on a district-level controller, implemented in the EnEff:Wärme:HybridBOT_FW project, which aims to optimise heat generation scheduling and minimise operating costs for the heat supply. A co-simulation framework models the interactions between thermal and electrical subsystems, allowing a comprehensive evaluation of operational strategies. The results show that the district controller facilitates load shifting between the electricity and heating sector, effectively utilising photovoltaic energy during peak generation hours while reducing reliance on district heating grid. Significant potential for load shifting is shown, particularly on days with high photovoltaic output and moderate heat demand. By synchronising power-to-heat operation with renewable energy generation, the controller improves the utilisation of locally generated energy and reduces high load peaks in the power grid. This study highlights the importance of advanced operational management in exploiting the synergies of sector coupling, thereby contributing to a more sustainable and resilient energy system. Sector coupling is a vital strategy for enhancing the efficiency and sustainability of energy systems by integrating various energy sectors.

1. Introduction

It is evident that the heat sector plays a pivotal role in the mitigation of greenhouse gas (GHG) emissions. In 2022, this sector accounted for approximately 50% of total final energy consumption and 38% of energy-related emissions [1]. In consideration of the sector's substantial contribution to aggregate GHG emissions, it represents a critical lever for the decarbonisation of the energy supply. In light of this, it is imperative to address the challenges associated with the transition to renewable energy systems, such as the fluctuating generation of energy and the temporal mismatch between energy demand and its availability [2]. District heating grids (DHGs) are emerging as a crucial solution for efficient heat supply in urban areas, especially in light of the need to transform the energy system and integrate renewable heat sources and unavoidable waste heat. The expansion of DHGs is expected to meet up to 71% of building heat demand in EU urban areas. By using access heat and low enthalpy renewable energy sources, district heating is an effective way to decarbonise the heat sector [3], [4], [5]. The integration of power-to-heat (P2H) technologies, such as heat pumps and electric boilers, enables innovative coupling between electricity and district heating grids. By establishing a hybrid energy system, it becomes possible to exploit synergies that enhance overall system efficiency and support the decarbonisation of the energy sector [6], [7]. However, this integration introduces significant operational complexity, requiring advanced control strategies capable of managing the dynamics of interconnected,



multi-energy infrastructures [8]. Current research highlights the value of co-simulation in the development and evaluation of such control strategies, particularly through the implementation of district level controllers that coordinate system operation across heat- and electricity-sectors. For example, Erdmann et al. (2021) present a flexible co-simulation architecture that integrates real-time analysis, forecasting, and sustainability-oriented control strategies. The approach is demonstrated in a district energy system scenario, where a low-carbon control strategy is implemented and evaluated for its operational benefits [9].

As recent studies underline the importance of co-simulation environments and advanced control strategies for managing the growing complexity of hybrid, sector-coupled energy systems, they also highlight the operational challenges and opportunities arising from decentralised, renewable-integrated infrastructures. Considering that each district is unique, it is crucial to identify the most appropriate strategy for each specific case, but also to develop transferable solutions to address a wide range of applications and needs within different districts.

This paper conducts a simulation-based analysis to evaluate the effects of sector coupling and operational optimisation within district heating and electricity grids. The study focuses on the integration of decentralised P2H technologies - such as heat pumps and electric heating elements - into DHG to form a hybrid energy system. A co-simulation framework is used to dynamically model the interactions between thermal and electrical subsystems and to assess the performance of a novel operational district control strategy. The analysis is based on the national research project, EnEff:Wärme:HybridBOT_FW, which aims to reduce the carbon emissions of the energy supply in a German town. The analysis investigates a district-level controller, implemented to optimise the scheduling of heat generation and minimise total heat supply costs. In addition, it explores the consequential effects on the electricity sector, examining how these optimisations influence energy consumption patterns. The findings provide valuable insights into the energy shifting potential of systems-oriented control, contributing to a broader understanding of sustainable energy management in urban environments.

2. Project scenario and district control strategy

The HybridBOT_FW project focuses on optimising sector-coupled heat supply at the district level. The consortium includes the AGFW, BBH Consulting AG, ENERPIPE GmbH (hardware supplier), IKEM, Stadtwerke Neuburg an der Donau (distribution system operator), and Fraunhofer IEE, and is set to continue until 2025. The project encompasses 111 district heating connections in a German town, primarily serving 82 residential buildings with varying heat demands due to their age. The DHG spans 4.14 kilometres, with a heat output of 1.32 MW and an annual demand of 2.3 GWh. The district is supplied by a combination of a DHG designed to meet large heating demands and 111 decentralised P2H-systems sized for hot water preparation. Each P2H-system also includes a thermal energy storage (TES) to store excess energy for later use, enhancing load shifting and peak load management. Moreover, each of the 111 P2H-locations includes a photovoltaic (PV) generator and a 10-kWh battery energy storage system (BESS). A central aspect of the project is a novel “district controller”, which (1) optimises the on/off-times of P2H systems and (2) regulates the supply temperature of the DHG, with the overall goal to reduce the district’s energy cost and increase consumption of local PV-power. The utilisation of Mixed-Integer-Linear Programming (MILP) facilitates the analysis of various parameters, including electricity and heat demand, thereby enabling effective energy management at the district level [12]. This paper analyses the impact of the district controller on the district’s electricity and heating grid state. The impacts are compared against a reference scenario in which the P2H-systems operate solely to cover the individual building’s heat demand. Specifically, the P2H-systems are deactivated when the maximum temperature in the building’s TES is reached and reactivated when the temperature subsequently drops.

3. Co-Simulation of Heat Supply and Electricity Grid

The optimised operation of the DHG and the P2H-systems in 82 buildings is analysed through a simulation-based study. The hybrid heat and electricity system of the district is digitally modelled, and sectoral interactions are represented by a co-simulation, as shown in **Figure 1**. First, the district’s electric power grid is emulated in the open-source software pandapower [13]. Second, the DHG is modelled in MATLAB Simulink, using the CARNOT toolbox [14]. Third, the 82 district buildings with 111 heating grid connections (each connection containing one TES and one P2H-system) are emulated in 4 separate MATLAB Simulink instances. The reason for splitting into 4 instances being, that one single instance with all buildings could not be executed due to CPU and memory constraints. Lastly, the district’s

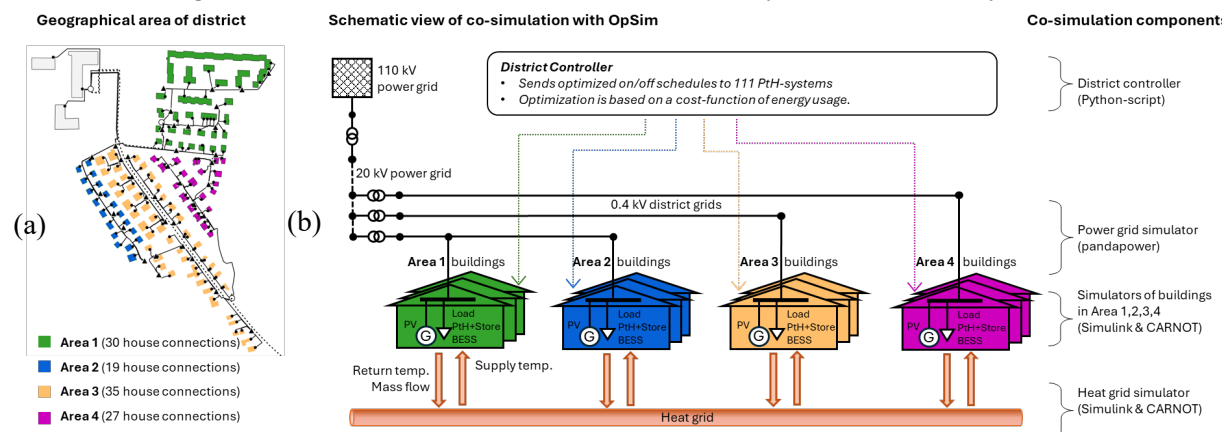


Figure 1. Geographical area of the district with number of heating grid connections (a) and schematic of the co-simulation (b).

energy flow is scheduled by the district controller, which optimises the heat supply at district level by planning suitable on/off times for each P2H-system. This controller is developed in Python with the Pyomo library. Its goal is to find suitable on/off times, such that the operating cost of energy consumption in the district (based on electricity and heat prices) is reduced as much as possible, whilst also promoting more P2H energy consumption from photovoltaic generation in the district [15].

Hence, there are 7 simulation components in total: 1 power grid, 1 heat grid, 4 building simulators, and 1 district controller. Their mutual data exchange is realised through the co-simulation environment OpSim [16] and can be summarised as follows:

- The building simulators send each building connection’s return temperature and mass flow to the heating grid simulator, from which they receive a supply temperature. Since some of the 82 buildings have multiple DHG connections, there exist 111 such interactions.
- The active power consumption of 111 P2H-systems in the building simulators is sent to the electric connection points in the power grid simulator. Hence, if any of the 111 P2H-systems are switched on/off, the electric consumption in the power grid in/decreases accordingly.
- The power grid simulator then calculates voltages and currents in the district’s electric grid. In this way, the active power flow over the district’s transformer can be modelled in detail, while also taking into account grid losses.
- Each of the 111 P2H-systems receives daily on/off schedules from the district controller. However, if the comfort-level in any building is too low (heat storage cooled down too much), the P2H-system may choose to ignore the set points until the building’s comfort is regained.

Table 1. Typical days selected for simulation.

	Day 1	Day 2	Day 3
Date	17/03/2021	01/04/2021	02/09/2021
Heat demand	High	Middle	Low
PV-power	Median-high	Median-high	Median-high

To reduce the overall computation time, especially during co-simulation, the project uses representative typical days. The year is divided into three groups based on low, medium and high heat demand, and further refined by selecting a day that is closest to the median of the upper half of the photovoltaic yield within each group. This results in a total of three typical days for the year, focusing specifically on days with median-high PV output to enhance the potential for sector coupling. The typical days and their indices are listed in **Table 1**.

4. Impact of the district controller on electricity grid and heat supply

The co-simulation results demonstrate the impact of a district-wide optimisation of the total costs of heat supply. **Figure 2** displays the different electric power flows in the district, for the exemplar typical day 2 (1 April). The dash-dotted lines mark the case when the district controller is active, as opposed to the solid lines, which are the reference case without district controller. It can be seen that the district controller focuses the electric P2H-consumption towards the centre of the day, as opposed to the reference case where P2H is active since the early morning hours. This also results in the BESS discharging more slowly during the evening hours, because there is less additional P2H-consumption to draw from the battery. It can also be seen that the progression of power consumption is slightly offset in time but corresponds to the PV yield in both scenarios. This is due to the additional load from the P2H systems, which reduces the feed-in from the PV installations and the negative load as feed-in reduction. Consequently, this mitigates the strain on the district's medium/low-voltage-transformers (MV/LV). **Figure 3** (a) displays the total electric power and heat consumption by the district for all typical days. The effect of the district controller on electric power can be seen by comparing the dash-dotted curves with the solid ones. In the heat consumption, this difference is explicitly plotted. It can be seen that the district controller causes a reduction of electric power consumption during the morning and evening hours. Moreover, because the P2H unit's on-times are moved towards the middle of the day, the district controller also causes a reduction of PV feed in peaks by utilising PV-power more for supplying the P2H-units (also see **Figure 4**). The surface area between each solid and dash-dotted curve is the amount of energy that is reduced; during times of positive consumption this is reduced load; during times of negative consumption, this is reduced feed in energy. **Figure 3** (b) shows this numerically.

For example, during winter day 1, the district controller reduces 4217 kWh of load peaks by turning off the P2H units. It must be noted that this energy now has to come from the DHG, to supply the district's heat demand. Conversely, during summer day 3, the district controller reduces consumption and feed in by almost similar amounts; meaning that the district's overall energy consumption remains fairly constant, but more PV energy is used to supply the P2H-units.

The lower panel of **Figure 3** (a) illustrates the heat injected into the DHG over time. The jagged lines are caused by the load profiles associated with each typical day. For each typical day (**Table 1**), the difference between the reference scenario without district controller and the scenario with district controller is plotted. Positive values indicate an increase in heat load, while negative values indicate a reduction. Electric load reduction of P2H-units during the morning and evening hours results in a corresponding heat load shift to the DHG, which now must supply the buildings more. Conversely, the

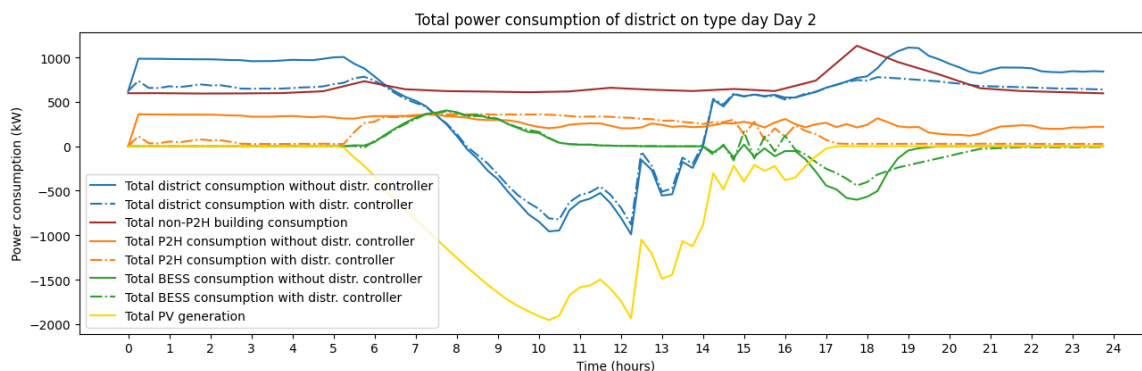


Figure 2. Total power consumption of the district with and without district controller.

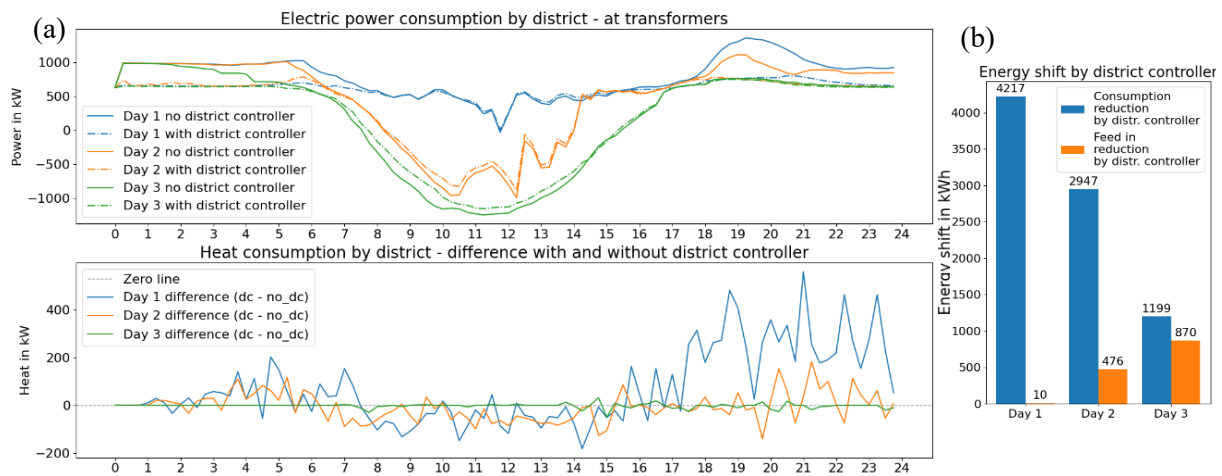


Figure 3. Comparison of total power and heat consumption in the district (a). Reduction of consumption and feed in by district controller (b).

use of PV-generation for supplying P2H-systems during the day results in a load reduction in the DHG. Also, load variations are less pronounced on typical days with lower heat demand.

Figure 4 shows the total electricity consumption by the 111 P2H-units in the district, subdivided into the fraction of energy provided by PV or power grid. By integrating these power values over time and adding them for all buildings with P2H-units in the district, the total energy supplied by PV and used by P2H could be established for each typical day (orange surfaces). Naturally, any P2H-energy demand that could not be covered by PV had to be supplied by the power grid (blue surfaces).

During the winter day 1 (19 January), the district controller did not increase PV energy used by P2H, but did reduce the total P2H-energy consumption by more than half. This energy must then be provided by the DHG, to ensure the building’s heat demands are met. On spring day 2 (1 April), the PV-consumption stayed fairly constant, but the total electric P2H-consumption was reduced. On the late summer day 3 (2 September) another result can be observed; the fraction of PV-energy feeding the P2H-units was almost doubled by the district controller. However, as the P2H-units were used less during the warmer summer months, the district controller did not reduce their total energy consumption as strongly, compared to the winter and spring day.

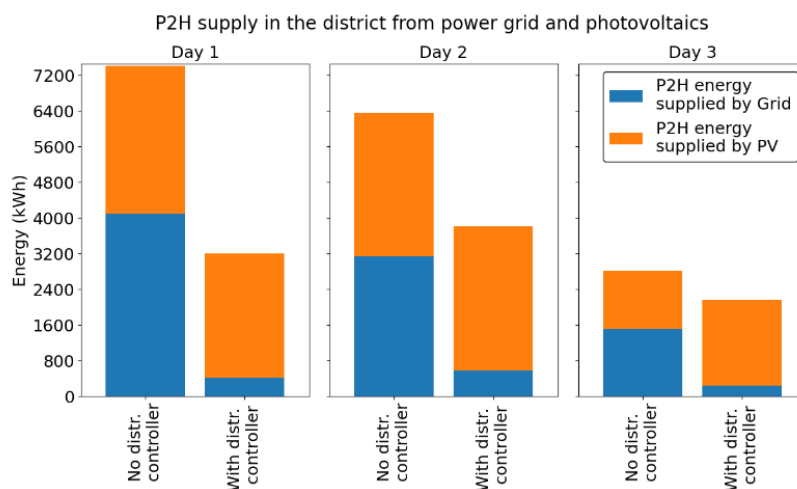


Figure 4. Electricity used to provide heat in the district by grid and PV for each typical day and scenario.

5. Conclusion

Sector coupling has the potential to increase the efficiency of the energy system. However, the use of P2H-systems needs to be coordinated in this context. The district controller developed increases the share of renewable energy in district heating. This paper showcased the impact of the district controller on the electricity and heating grid, illustrated by a specific district case.

The implementation of the district controller facilitates load shifting between the electricity and heating sectors. During the morning and evening hours, the electricity sector is relieved by a decreased P2H-consumption, while the DHG is met with a higher demand to supply the building's heat needs. Conversely, during the day, the generated PV-power is used to supply heat via P2H-systems more, while reducing the reliance on the DHG. In addition, on days with a high average PV-output and moderate to low heat demand, such as typical days 2 and 3, the feedback of PV electricity to the medium voltage level is reduced. As a result, locally generated energy is used more effectively, reducing the risk of grid overload from simultaneous PV generation.

A comparison of the electricity consumption of the P2H-systems with and without the district controller shows that less heat is supplied by the P2H-systems with the controller, indicating a load shift towards the heating network. By synchronising the P2H operation with the PV-output via the district controller, the share of renewable sources can be almost doubled during late summer typical day 3. The load shifting effect generated by the district controller refers to the balance between heat demand and renewable energy supply. With high levels of renewable generation, load shifting is only possible if there is a corresponding demand for heat. In particular, the highest potential for load shifting and reduction of greenhouse gas emissions through sector coupling occurs on the typical day 2 (1 April). The results indicate that the synergies of sector coupling can only be effectively exploited when coupled with operational management, otherwise they may place additional burdens on the electricity grid.

This work examined results based on typical days with a median-to-high PV yield. However, a meaningful assessment of the district controller's potential should be conducted over the course of a whole year in order to consider the potential gains on less sunny days and the inter-daily effect of the thermal storage.

Following this analysis, the District Controller optimises operating costs. However, to comprehensively assess the cost-effectiveness of the system as a whole, investment costs will also need to be considered in future evaluations.

In a renewable energy system characterised by stochastic and less predictable generation and consumption, intelligent control of systems is essential for flexible energy use across sectors. Implementing control mechanisms at the district level enables scalability to multiple districts, promoting a bottom-up approach. Ultimately, the effective integration of sector coupling through intelligent district management not only enhances energy efficiency and sustainability but also paves the way for a resilient and adaptive energy system in the face of future challenges.

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