International Journal of Sustainable Energy Planning and Management Vol. 49 2026 26–36

International Journal of
Sustainable Energy Planning and Management

Influence of sector coupling on a district heating system in a German town: thermal simulation and comparison of different supply scenarios

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ABSTRACT

District heating grids (DHGs) offer substantial potential for decarbonising the heating sector, which accounts for around 40 % of Europe's total energy consumption. Although DHGs are a mature technology, the integration of renewable energy (RE) remains limited. This study evaluates Hybrid Network Solutions (HNS) through a one-year simulation of three heat supply scenarios in a southern German town. Two innovative HNS concepts incorporate rooftop photovoltaic (PV) systems and decentralised thermal energy storage (TES) to enable sector coupling via electric heating elements and air-to-water heat pumps (HPs). Scenario 1 integrates heat supply through a DHG with decentralised Power-to-Heat (P2H) units, enabling greenhouse gas (GHG) reductions by utilizing surplus PV electricity. Scenario two introduces a dual-grid structure with a low-temperature network supplied by a large groundwater heat pump and a high-temperature DHG using waste heat. While this configuration reduces final energy demand, it results in higher GHG emissions due to reliance on grid electricity with a high primary energy factor. The findings highlight the efficiency potential of HPs and the importance of aligning heat sector electrification with power sector decarbonisation. HNS concepts can serve as scalable models for sustainable district heating, provided that a renewable electricity supply and intelligent operational strategies are ensured.

Keywords

District heating networks;
Hybrid networks;
Sector coupling;
Power-to-heat;
Thermal simulations

http://doi.org/10.54337/ijsepm.11195

1. Introduction

The reduction of greenhouse gas emissions (GHG) in the atmosphere is currently one of the most relevant global challenges. Through the Federal Climate Change Act, Germany has set national targets of at least 88 % reduction in GHG emissions by 2040 and of neutrality by 2045 [1,2]. The heating sector is of decisive importance to achieve these objectives, since it accounts for about 40 % of the GHG emissions related to the energy sector both in Germany and in Europe [3].

In this context, district heating grids (DHGs) emerge as a key technology, considering that 14 % of the space heating demand in Germany is covered by these systems [4]. Moreover, the concepts of hybrid energy networks and smart energy systems, defined as systems where electricity, thermal, and gas networks are combined and integrated in a synergic way, have gained significant attention as a pathway to optimise the overall energy system and increase its flexibility [5,6].

Hybrid networks can be understood as configurations in which physically separate power and DHGs are functionally interconnected through various coupling technologies, enabling coordinated generation, transport and consumption [7]. The integration of district heating within hybrid energy systems is particularly promising to speed up the decarbonisation of the heating sector, thanks to the exploitation of temporary renewable surplus generation through sector coupling [8].

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Received 30.11.2025 | Accepted 05.05.2026 | Published 19.06.2026

List of Abbreviations

COP	*Coefficient of performance*
CHP	*Combined heat and power*
DHG	*District heating grid*
GCHP	*Ground coupled heat pump*
GHG	*Greenhouse gas emissions*
GWHP	*Groundwater heat pump*
HNS	*Hybrid network solutions*
HP	*Heat pump*
LTDH	*Low-temperature district heating*
P2H	*Power-to-heat*
PV	*Photovoltaic*
RE	*Renewable energy*
TES	*Thermal energy storage*

Sector coupling is defined as the integration of different energy sectors including electricity, heat, and transport: the energy provided by one sector is used by another one and can be converted again [7]. Surplus renewable electricity can be converted into heat through power-to-heat (P2H) technologies, including electric boilers, heat pumps (HPs), and resistance heaters, and can then be stored in thermal energy storage (TES) systems, balancing energy demand and offer.

The integration of HPs into DHGs has become a central strategy, as reported by the IEA Heat Pumping Technologies Annex 47, which surveyed 24 realised HP installations with a total capacity of 108 MW across 14 European DHGs, identifying both technical barriers and innovative solutions for their deployment [9]. Compared to other P2H options, HPs are particularly suitable for longer, more frequent and lower renewable energy (RE) surpluses, due to the high coefficient of performance (COP) [10]. Load shifting can be planned by controlling heat generators based on residual load, i.e. the difference between the energy demand and the electricity supplied by RE [11].

The recent spread of the fourth generation of district heating systems is a further opportunity for facilitating the implementation of hybrid network solutions (HNSs) [12,13]. The reduction of the DHG supply temperature allows for decreased heat losses and thermal stress in the pipes, and for a higher integration of waste heat and RE sources [5]. However, barriers remain in the implementation of these systems, as highlighted by Pellegrini et al. [14].

Scientific literature reflects the growing interest for the topics related to HNSs. The IEA DHC Annex TS3 presents a comprehensive overview about these energy networks, discussing the available technologies for sector coupling, providing decarbonisation perspectives and collecting some of the most relevant real-world hybrid energy systems [5].

Schmidt et al. carried out a SWOT analysis for HNSs, highlighting the opportunities given by digitalisation, TES and decentralisation, while also pointing out the threats represented by the increased electricity demand and uncertainty in the current world situation [15]. Sorknæs compared three different HNSs for both Austria and Denmark, discussing the potential of direct electrification of DHGs by means of electric boilers and HPs [16]. Csontos et al. combined door-to-door surveys, GIS-based resource mapping and heat demand analysis to identify suitable areas for multi-source DH developments in a Hungarian region [17].

Mikulandric et al. developed a mathematical model for a hybrid network integrating a combined heat and power (CHP) plant, a biomass boiler, HPs and TES systems, and highlighting cost reductions due to the integration of RE in the heat supply [18]. Talebi et al. compared two dynamic optimisation scenarios for an existing hybrid community DHG integrating central TES and supplied by gas and biomass [19]. Capone et al. developed a steady-state model of a DHG in Northern Italy, discussing the possibilities for integration of large-scale HPs, and Siddiqui et al. investigated the operation of a DHG integrated with a large ground-source HP and central TES [20,21]. Pieper et al. demonstrated the feasibility of integration of large-scale HPs with low-temperature supply in Tallin’s DHG [22]. Holmér et al. highlighted the beneficial effect of including TES in DHG, facilitating solar heating and power-to-heat technologies integration [23].

Against this background, this study investigates different heat supply options for a district in the Bavarian town of Neuburg on the Danube, carried out within the research project “EnEff:Wärme: HybridBOT_FW” [24]. An overview of the project was already presented in Cadenbach et al. [25], reporting the first results obtained from the co-simulation of the integrated operation of the thermal and electricity sectors, and considering adequate control strategies for the electricity grid and the district.

Instead, this paper presents the comparison of three different supply scenarios, focusing on the implications for the heating sector. Two scenarios incorporating an HNS have been developed for a specific urban district (see Section 2.1) and subjected to a comparative, simulation-based analysis. The analysed heat supply scenarios (detailed in Section 2.2) are founded on DHG and flexible sector coupling technologies, such as electric heating elements and HPs, which are integrated with decentralised TES within buildings. In response to the need for load shifting, the operation of these P2H units is aligned with the intermittent supply of RE sources, particularly photovoltaic (PV) generation. Indeed, the combination of an existing centralised DHG with decentralised building-level P2H units, decentralised TES, and rooftop PV surplus utilisation remains underexplored in the literature.

The objective of this study is therefore to compare three heat supply scenarios for a real district and to assess how decentralised sector coupling technologies can complement an existing DHG with regard to final energy demand, GHG emissions and the utilisation of coupling technologies.

The focus on local PV surplus is motivated by the intention to analyse a technically feasible form of local sector coupling between electricity and heat within the district. In this way, rooftop PV generation is not only treated as a generic RE source, but as a local flexibility option that can be directly linked to decentralised P2H operation and TES charging at building level. The investigated concept thus follows a bottom-up approach at district level, aiming to utilise as much locally generated energy as possible directly within the district and, in particular, within the buildings through decentralised P2H units and TES before surplus electricity is exchanged with the public grid.

Rather than aiming to immediate practical implementation, the proposed HNSs focus on the transferable transformation concepts of existing DHGs by enhancing the usage of RE sources. The scenarios also explore the potential of flexible grid temperatures and temperature reduction. The HNSs are compared to a reference scenario in which district heat is supplied exclusively through a DHG. Through this comparative approach, the study analyses the performance of three supply scenarios for an existing district, with a particular focus on the sector coupling role of decentralised P2H units, TES, and rooftop PV surplus utilisation in comparison with a conventional DHG supply concept.

2. Hybrid supply concept and methodology

The methodological framework addresses the technical integration of hybrid heat supply systems within an existing district heating context. It combines centralised DHG with decentralised TES systems and sector coupling technologies, including electric heating elements and HPs, supported by PV surplus utilisation. Key design aspects include dynamic supply temperature control, hydraulic separation between subsystems, and decentralised TES for peak load management. The proposed configurations are modelled using dynamic simulation tools to analyse thermic interactions and operational flexibility under varying load and generation conditions.

2.1 Description of the district

The case study district is situated in Neuburg an der Donau, a town in Bavaria, Germany. As illustrated in Figure 1, the area is predominantly characterised by residential buildings, with a few commercial structures located in the northwest, including facilities operated by the municipal utilities and a kindergarten. For the purposes of this analysis, only the residential buildings outlined in red are considered.

The residential buildings vary in type, age and associated energy standard. They are mostly single- or double-family houses, but there are also four multi-family buildings, with up to 16 housing units. The yellow buildings in the north are new builds that comply with the German KfW55 energy standard, with a combined heating load of 635 kW. In contrast, the buildings marked in blue were constructed between 1940 and 2003 and have a total heating load of 581 kW (see Table 1).

For the existing buildings in the southern area, the annual heat demand is based on actual gas consumption data. The average annual heat demand of 20,7 MWh/a per building results in part from the fact that some buildings were aggregated into larger units for the analysis. For the new buildings in the northern area, the annual heat demand was estimated using a specific heat demand of 35 kWh/(m²a).

The diversity in construction periods suggests the presence of heterogeneous heating systems, each requiring different supply temperatures. In new buildings, underfloor heating typically operates at approximately 35 °C, whereas existing buildings predominantly rely on radiator systems requiring supply temperatures of around

65 °C. Furthermore, to comply with hygiene standards, domestic hot water (DHW) must be maintained at a minimum of 60 °C. Consequently, the district presents an interesting case study for investigating the feasibility and implications of transitioning to a hybrid energy system.

Given that Neuburg an der Donau hosts several industrial companies with high-temperature process requirements, the local municipal utilities currently operate two distinct DHGs, which are owned by the town. The first grid supplies high-temperature heat to industrial users, while the waste heat generated is utilised to feed a second, lower-temperature DHG operating at approximately 90 °C.

2.2 Description of the supply concepts

Two supply scenarios featuring an HNS are developed and compared with a reference scenario. A comparative overview of the relevant parameters is presented in Figure 2.

In the reference scenario, heat is provided only through a DHG operating at a constant temperature of 80 °C. The heat source is the existing DHG, from which it is thermo-hydraulically separated by a heat exchanger. This approach allows for flexible adjustment of the supply temperature. The supply temperature of 80 °C ensures that the buildings' heat demand, including space heat and DHW, is fully met by the DHG. All buildings are equipped with decentralised thermal water storage tanks, sized between 1,000 and 3,000 litres according to the heating load, enabling peak shaving. Across all buildings, this results in a total storage volume of approximately 90 m³. To guarantee comfort and hygiene, DHW is supplied separately from the storage tank through a freshwater station.

The two hybrid scenarios (1 and 2) were developed as district-based supply concepts that aim to maximise the local utilisation of PV electricity within the district before surplus electricity is exchanged with the public grid. The focus on rooftop PV is motivated by the possibility of using already built-up areas for local RE generation without requiring additional land. Against this background, the investigated supply concepts address the question of how this locally generated electricity can be integrated and utilised as efficiently as possible within the district heat supply while minimising electricity exchange via the public grid. In both scenarios, the existing DHG is complemented by decentralised sector coupling technologies at building level, in particular P2H units and HPs combined with TES.

The development of the supply variants also considered that electricity exchanged via the public grid is generally associated with additional charges, whereas electricity used locally within the building is not subject to the same conditions. These economic implications were considered qualitatively but not quantified in the present study. In both hybrid scenarios, decentralised sector coupling technologies, such as electric heating elements and air-to-water HPs, are used to reheat the decentralised TES. The energy for reheating is provided by surplus PV power from rooftop solar installations on each building. PV electricity is first used to cover the buildings' household electricity demand, and only the remaining surplus is used for decentralised P2H operation and, in Scenario 2, for a central groundwater heat pump (GWHP).

For the sizing of the rooftop PV systems, a largely maximised use of the available roof areas was assumed. The installed PV capacity was estimated using a simplified calculation approach based on the building areas and several reduction factors according to Fritz et al. [27]. In total, this results in an installed PV capacity of 1.4 MWp within the district. A substantial share of this capacity is associated with the large multi-family buildings located in the northern part of the district. The coupling technologies are sized according to the DHW demand based on the relevant DIN EN 15450 standard [28]. Overall, the installed electrical capacity of the decentralised electric heating elements and HPs is 430 kW. Scenario 1 prioritises the local use of rooftop PV surplus within the buildings. Besides the decentralised sector coupling technologies, Scenario 1 is similar to the reference scenario: the entire district is supplied by a single DHG. Moreover, the DHG operates with a floating temperature level that adjusts according to the outside air temperature [29]. This means that the supply

Table 1: Relevant parameters describing the boundary conditions within the supply district.

Residential area	Year of construction	Heating peak load	Annual heat demand	Number of buildings
North	New construction	635 kW	740 MWh/a	25
South	1940 – 2003	581 kW	1182 MWh/a	57

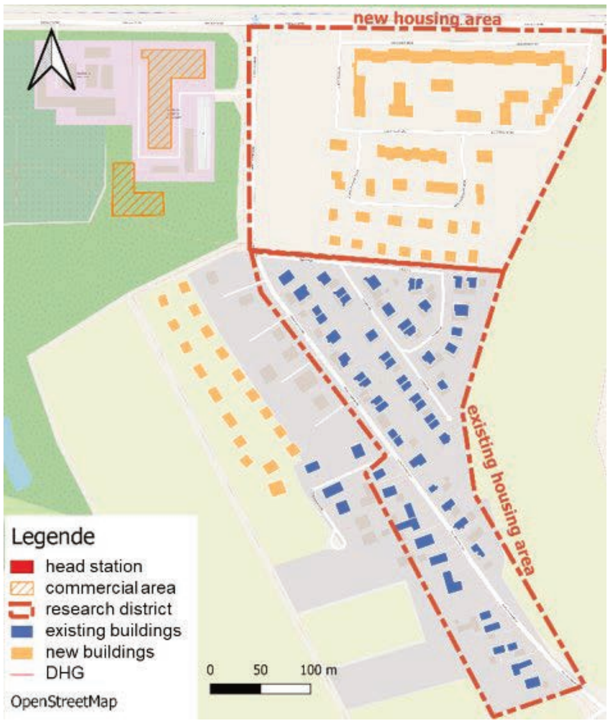

Figure 1: Map of the considered district showing new build and existing residential building (own representation based on OSM [26]).

temperature varies between 80 °C during the coldest periods and 75 °C in warmer months. In summer, when heat demand is low, the DHG is temporarily shut down, and heat is provided exclusively by decentralised P2H units. As a result, the grid can adapt to fluctuating demand while reducing distribution heat losses [13]. Scenario 2 follows the same district-based approach and also includes decentralised P2H units and TES supplied by rooftop PV surplus at building level. In addition, it extends the supply concept through a central GWHP and a differentiated DHG structure with two temperature levels. The district heat supply is therefore divided into two DHGs in order to better match the different temperature requirements of newly developed and existing building areas (see Section 2.1).

The existing housing stock remains connected to a DHG operating with variable supply temperatures between 70 °C and 80 °C, similar to Scenario 1. Conversely, the second DHG is operated at 45 °C and supplies the new development area through the GWHP. This configuration enables a substantial reduction in the supply temperature of the second DHG, thereby leading to benefits associated with low-temperature district heating (LTDH), such as reduced heat losses and improved overall system efficiency [12,13]. As in Scenario 1, decentralised P2H units and TES remain part of the supply concept and continue to enable the local use of rooftop PV surplus at building level.

The central HP was chosen by taking into account different local sources at almost constant temperature, in order to ensure an efficient operation. The adoption of a ground coupled heat pump (GCHP) was discarded after a first dimensioning made with the ASHRAE method resulting in a requirement of more than 300 borehole heat exchangers, meaning that high drilling costs would have been required. Moreover, the ground regeneration problem must be faced if the GCHP is only exploited for heating purposes [30].

Therefore, a groundwater heat pump (GWHP) with water reinjection is implemented as the heat source for the new development area, since the geographical conditions of the site are highly suitable for this technology [31]. This solution also offers high replicability for similar towns, which makes it particularly attractive for broader implementation.

The electricity required by the GWHP is expected to be supplied by the PV power that exceeds the buildings' electricity demand and is not used to supply the coupling

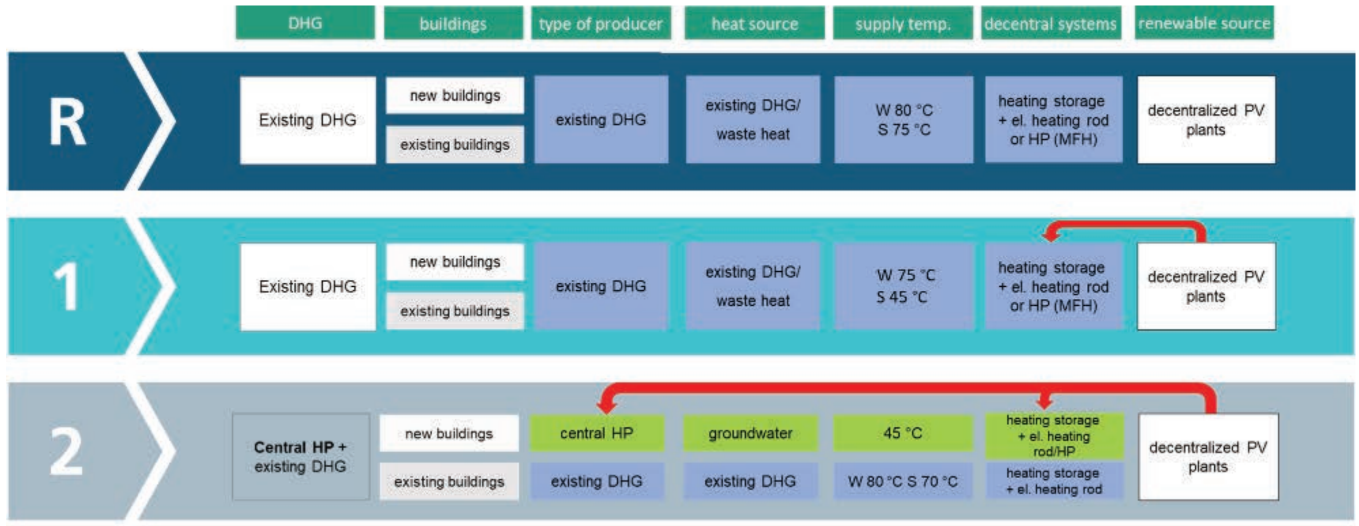

Figure 2: Comparative overview of the relevant parameters of all heat supply scenarios.

technologies connected to the decentralised storages. If this residual PV is not sufficient, the central HP is going to be supplied partially by the electric grid. To ensure stable operation of the HP, a central TES tank is integrated as an interface between the HP and the DHG. This configuration provides hydraulic separation of the two subsystems and enables supply at the desired temperature.

2.3 Modelling the energy supply

All scenarios are modelled in MATLAB Simulink (2021b version) [32], which is a graphical environment for dynamic simulations of TES. In particular, the conventional and renewable energy systems optimisation toolbox (CARNOT) is used, since it is a Simulink library for modelling thermal and hydraulic components such as heat exchangers, storages, heat pumps, pipes and valves [33]. The models consist of interconnected blocks that exchange input and output signals representing the parameters used in the internal calculations of each block.

All simulations were conducted over one full year at an hourly resolution, with heat demand, DHW demand, weather data, and PV generation represented by corresponding hourly input time series. Due to the high computational effort, the decentralised TES models and the DHG models were simulated in parallel in separate MATLAB instances. During the simulation, the relevant boundary conditions and state variables were exchanged between these model parts through the software OpSim [34], so that the overall model still represents one integrated annual system analysis. A variable-step solver was used, meaning that the calculation step size is automatically adapted to the system dynamics and error tolerances.

The heat and DHW demand are simplified and provided as an input time series representing the discharge from the decentralised thermal storages. The DHW demand was estimated based on the average daily consumption using a statistical approach implemented through the DHWcalc tool [35]. The installed capacity of the decentralized sector coupling technologies is sized according to the DHW demand to avoid oversizing and minimize resource utilization.

The operation of the technologies follows a technical control logic rather than an economic optimisation. Decentralised P2H units are operated when PV surplus is available, up to their maximum installed capacity and within the operational limits of the connected TES. The charging of the decentralised TES is additionally controlled in order to avoid overcharging and to maintain the required storage temperature levels. If the heat provided by the decentralised P2H units is not sufficient, the remaining heat demand is supplied by the DHG. The results of the simulations are analysed in Section 3.

3. Simulation results and discussion

Figure 3 shows the monthly heat supply for Scenario 2, disaggregated by DHG and decentralized P2H units. Due to the high heating demand in winter, a classic seasonal distribution pattern emerges. During the summer months, heat is almost exclusively provided by decentralised P2H units. In the transitional months of May and September, the share of P2H, and thus of renewable PV energy in the heat supply, accounts for over 50 %. However, this effect is limited in relation to the annual heat demand, given that there is high heat demand in the winter months and the DHG accounts for a significantly higher proportion of the heat supply.

The bar chart in Figure 4 shows a comparison of the total final energy supplied in all scenarios. In the reference scenario, the DHG is the only heat source, whereas in the other two scenarios, the heat supply is divided between different technologies, depending on whether it is supplied by electricity from the grid or PV plants. The total final energy values are 2689 MWh/a, 2490 MWh/a and 2038 MWh/a for the reference, first and second scenarios respectively.

In Scenario 1, only a marginal share of the annual heat demand (131 MWh) is supplied by PV-driven decentralized P2H units. Concurrently, the system's total energy requirement decreases by 199 MWh per year (7 % compared to the reference scenario), primarily due to reduced heat supply by the DHG, which lowers distribution losses.

Scenario 2 demonstrates the highest relative contribution of decentralized P2H units to overall heat demand, with a 24 % decrease of final energy demand compared to the reference scenario. This outcome is driven by the fact that one of the DHGs operates at a supply temperature below the 60 °C threshold required for hygienic DHW preparation. Consequently, P2H units must operate more frequently and exhibit limited flexibility in adapting to variable PV generation.

Among all three configurations, Scenario 2 supplies the lowest total energy demand through DHG. This is mainly due to the use of environmental heat by the large-scale heat pump, which reduces the externally supplied final energy and reflects the high efficiency of this system design.

Figure 5 illustrates the variation in GHG emissions across the analysed energy supply scenarios. Both the reference case and Scenario 1 are predominantly supplied by DHG, resulting in emissions that scale proportionally with this source. Owing to the integration of PV generation, Scenario 1 exhibits 12 % lower GHG emissions compared to the reference configuration.

The calculations assume an average primary energy factor (PEF) of 0.4 for German DHG [36] and an equivalent emission factor of 120 g CO_2 per kWh of heat, as shown in Table 2, in order to provide a generic benchmark and not to overrepresent the particularly local DHG setup. For electricity from the public grid, including the electricity supplied to the central HP, the assessment is based on the standardised factors applied in Germany for building energy evaluation according to the GEG [37], thereby reflecting the practical assessment approach currently used in this context. Each PEF value was multiplied by the final energy supplied by the related source, computing the primary energy. Then,

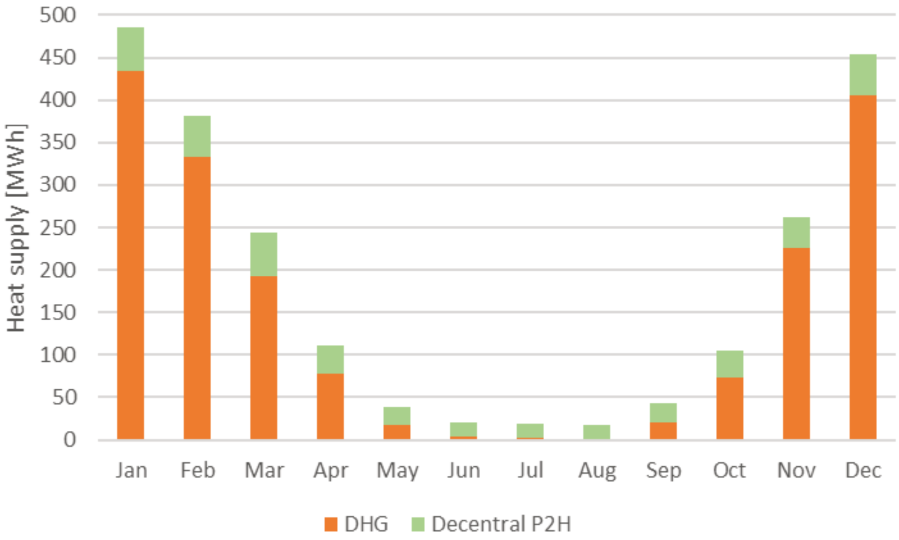

Figure 3: Monthly heat supply in Scenario 2, disaggregated into DHG and decentralised P2H units.

GHG emissions were obtained by multiplying the CO_2 equivalent for each source by the respective primary energy.

In contrast, Scenario 2 records more than twice the emissions of the reference case, amounting to 291 tCO_2-eq/a. This increase is primarily attributable to the inclusion of grid electricity for operating decentralized P2H units and the large-scale heat pump. Conversely, emissions associated with DHG feed-in are lowest in Scenario 2, at only 69 tCO_2-equivalent. This indicates that the comparatively high total emissions of Scenario 2 are mainly driven by the current carbon intensity of grid electricity. Under a fully decarbonised electricity supply, Scenario 2 would therefore be expected to have the lowest overall GHG emissions among the analysed scenarios. These findings underscore the strong dependency of overall GHG performance on the share of renewable energy within the electricity mix and its corresponding emission intensity.

4. Conclusion and outlook

The analysis demonstrates that sector coupling through the integration of PV generation and P2H technologies is a promising option for reducing primary energy consumption and supporting the decarbonisation of district heating systems. At the same time, the results indicate that the performance of such concepts depends strongly on the system design and on the carbon intensity of the electricity supply. In this context, the implementation of large heat pumps offers considerable efficiency potential but still faces important challenges under current boundary conditions.

Scenario 1 highlights the benefits of seasonal network shutdowns and decentralized P2H operation. In the present case study, this results in lower final energy demand, improved utilization of locally generated PV electricity, and reduced DHG operation during periods of low heat demand. At the same time, Scenario 1 reduces the need for electricity supply from the public grid, since locally generated rooftop PV electricity is directly utilised within the buildings by decentralised P2H units.

The results further show that the decentralised integration of P2H units and TES can support the local utilisation of rooftop PV surplus and provide additional operational flexibility within a DHG-based supply concept. In the investigated district, this is particularly reflected in lower distribution losses and in the

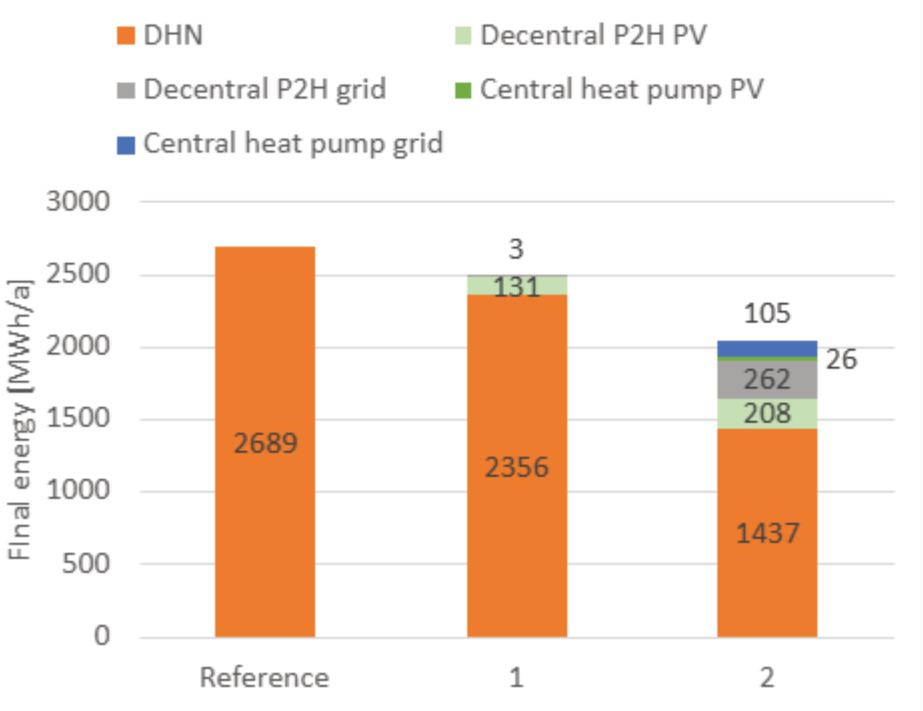

Figure 4: Comparison of the final energy demand of the supply scenarios, disaggregated by generation plant and electricity supply from the grid or PV system.

Table 2: Overview of the parameters used for the primary energy factor and equivalent CO_2 emissions.

	PEF	CO_2eq [g/kWh]
DHG (source [36])	0.4	120
Power grid (source [37])	1.8	372
Power grid for central HP (source [37])	1.2	372

possibility of shifting part of the heat supply to decentralised technologies. In addition, Scenario 1 suggests that, in areas where rooftop PV is available, decentralised P2H units can already support a stepwise decarbonisation of heat supply in an existing DHG, even before the electricity sector is fully decarbonised and before the central district heating infrastructure is completely transformed.

Scenario 2 highlights both the efficiency potential and the current limitations of a more advanced district-based transformation concept. While the differentiated low-temperature DHG structure and the integration of a central GWHP reduce the final energy demand, the scenario also reveals critical challenges, including unmet DHW requirements and an increased reliance on decentralised P2H systems, which lead to high electricity consumption.

Consequently, this efficiency advantage is not yet reflected in the GHG balance, because the additional electricity demand is assessed using the current grid electricity mix. Under the boundary conditions applied in this study, Scenario 2 therefore combines lower final energy demand with higher GHG emissions, although this would be expected to change with a more strongly decarbonised electricity sector.

From a broader perspective, the investigated concept can also be understood as a bottom-up flexibility approach at district level, aiming at the greatest possible local utilisation of electricity generated within the district. In this way, such concepts may reduce the need for electricity exchange via the public grid and could, in the longer term, contribute to avoiding or delaying grid reinforcement.

Future work should therefore not only consider the economic performance of the investigated supply scenarios but also assess the practical feasibility of local PV-based sector coupling with regard to the regulatory and economic framework conditions associated with electricity exchange via the public grid. In addition, further

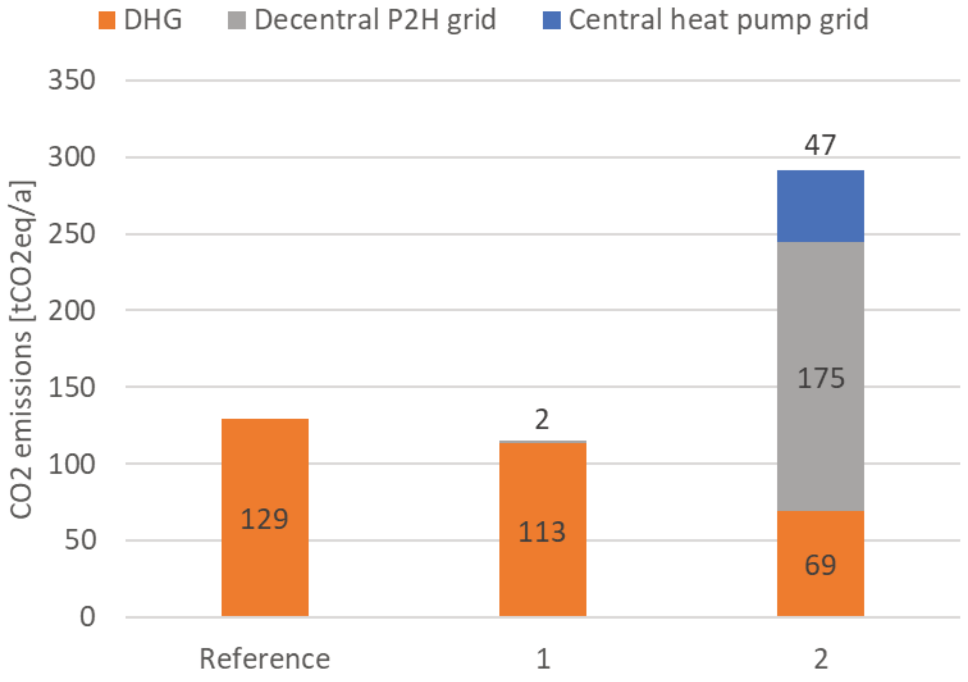

Figure 5: Comparison of the equivalent CO_2 emissions of the supply scenarios, referenced to the source of supply: DHG or electricity grid.

work within the broader research project addresses intelligent control strategies that combine economic optimisation with load-shifting approaches in order to align additional electricity demand with periods of high renewable generation. These questions, however, are beyond the scope of the present paper. In this context, energy community approaches and business models that incentivise PV self-consumption and decentralised storage may further improve the practical feasibility of such concepts.

Finally, the success of such concepts depends on the parallel decarbonization of the electricity sector. Heat pumps and P2H units offer substantial efficiency gains compared to direct electric heating, yet their sustainability hinges on the availability of low-carbon electricity. Coordinated strategies for heat and power decarbonization are therefore indispensable. If these conditions are met, the investigated supply concepts could provide a useful basis for the gradual transformation of existing high-temperature DHG systems and for guiding similar developments in other urban districts, paving the way toward a more integrated and climate-neutral energy system.

Acknowledgements

This work presents results from the project "EnEff:Wärme: HybridBOT_FW" funded by the German Federal Ministry for Economic Affairs and Energy under grant no. "03EN3041A". The authors thank ENERPIPE GmbH and Stadtwerke Neuburg an der Donau for providing information on the district and thermal energy system technologies. The responsibility for the contents of this publication lies solely with the authors. This article belongs to the special issue of the 2025 Smart Energy Systems conference, Copenhagen, 16-17 September 2025.

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