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Supply-Side Optimisation and P2H Sizing for a 2040 Net-Zero District Heating System: The Kapfenberg Case

Transformation Planning With Industrial Waste Heat and Sector Coupling

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Abstract. This paper presents a techno-economic optimisation of supply-side transition pathways for the district heating system of Stadtwärme Kapfenberg GmbH (Austria), aiming at full decarbonisation by 2040. Conducted within the SUPPORT DHC project, the study assesses how industrial waste heat, renewable heat options, and Power-to-Heat (P2H) can be combined to provide cost-efficient and reliable heat supply under evolving boundary conditions. A detailed energy system model was implemented in energyPRO and optimised at hourly resolution over a full year using validated demand profiles and operator-specific constraints, including source availability, maintenance schedules, technology priority constraints, operational cost parameters, and fixed installed capacities for existing assets.

The analysis pursues two objectives: one with identifying cost-optimal supply portfolios for the current and planned expanded system, and the other with sizing P2H under two operational modalities (PV-only and PV plus grid electricity – grid import is permitted only when day-ahead prices are at or below a threshold; proxying hours with high renewable availability and/or low marginal emissions) within predefined capacity ranges.

Across the analysed scenarios, industrial waste heat remains the dominant component of the cost-optimal portfolio. For the PV capacities considered, PV-only P2H exhibits a limited system-wide impact, indicating that achievable benefits depend strongly on local generation scale. In contrast, grid-enabled P2H improves economic performance and operational flexibility under the applied electricity price threshold formulation. Minimum levelized cost of heat occurs at approximately 2 MW P2H capacity with a grid price threshold of around 40 €/MWh; beyond this point, marginal benefits diminish as low-price operating hours saturate.

The paper provides decision support for municipal utilities by demonstrating an optimisation-based heat production planning workflow that informs EED-aligned transformation and investment planning for accelerated integration of industrial waste heat and low-grade renewable heat, with sector-coupling options assessed to strengthen operational feasibility.

Keywords: District Heating Decarbonisation, Power-To-Heat, Waste Heat Integration, Techno-Economic Optimisation, Sector Coupling

1. Introduction

Decarbonising Europe's District Heating and Cooling (DHC) systems requires the accelerated integration of low-grade renewable energy (RE) and waste heat (WH) while maintaining affordability and security of supply. This objective underpins the SUPPORT DHC project, which aims to overcome key barriers faced by DHC operators, including high upfront infrastructure requirements, substantial implementation efforts, and the practical integration of technologies that are often novel to incumbent high-temperature systems. Moreover, the forthcoming definition of "efficient district heating and cooling" under Article 24 of the revised Energy Efficiency Directive (EED) provides a policy trajectory towards 2050 and reinforces the need for holistic transformation planning supported by actionable investment roadmaps [1].

Modernisation and retrofitting of District Heating (DH) systems can deliver substantial reductions in fossil fuel consumption and greenhouse gas emissions, with reported CO_2 savings reaching up to 40% in practical applications [2]. Achieving such outcomes necessitates robust supply-side optimisation under real operational constraints, since demand variability, source availability, and operational practices may deviate significantly from design assumptions. Integrating RE and WH is hindered by spatial and temporal mismatches between heat availability and demand. District heating networks help overcome spatial constraints by connecting sources and consumers, while thermal energy storage and optimised dispatch are required to balance temporal variability and provide operational flexibility [3].

Within this European context, Stadtwärme Kapfenberg GmbH, which operates the DH network of Kapfenberg in the centre of Austria, has aligned its long-term strategy with Austria's climate neutrality objectives, targeting a progressive transition of its heat supply portfolio towards renewable and low-carbon sources. Evidence from integrated district-scale planning indicates that coordinated supply- and demand-side measures, combined with strategic network adaptation and expansion, yield cost-effective and carbon-efficient decarbonisation pathways [4]. The Kapfenberg case thus provides a representative testbed to evaluate how advanced planning and optimisation can support a transition towards a DH system predominantly based on RE and industrial WH.

In this setting, sector coupling via Power-to-Heat (P2H) represents one potential flexibility option within integrated heat production planning. By linking the electricity and heat sectors, P2H can utilise renewable electricity under defined operating conditions and contribute to operational flexibility, particularly when combined with thermal energy storage. However, the techno-economic value of P2H is strongly context-dependent and should be assessed within the full supply portfolio and operator constraints [5].

Accordingly, this paper develops a techno-economic assessment embedded in a municipal transition pathway, with three objectives: (i) to evaluate cost-optimal supply portfolios for the current and planned DH configuration of Kapfenberg; (ii) to determine suitable P2H capacities under PV-only and grid-enabled operational modalities using hourly optimisation; and (iii) to derive decision-relevant insights that support stepwise, EED-aligned transformation and investment planning towards full decarbonisation by 2040.

2. Case Study Description: Stadtwärme Kapfenberg

The case study addresses the heat production planning of the district heating system operated by Stadtwärme Kapfenberg GmbH (*Figure 1*). The overarching objective is to support the utility in developing a coherent transformation plan that enables the systematic integration of renewable energy sources and waste heat, in line with the planned expansion and long-term decarbonisation of the DH network. The analysis is carried out within the framework of the SUPPORT DHC project and focuses on supply-side transition pathways under realistic operational conditions.

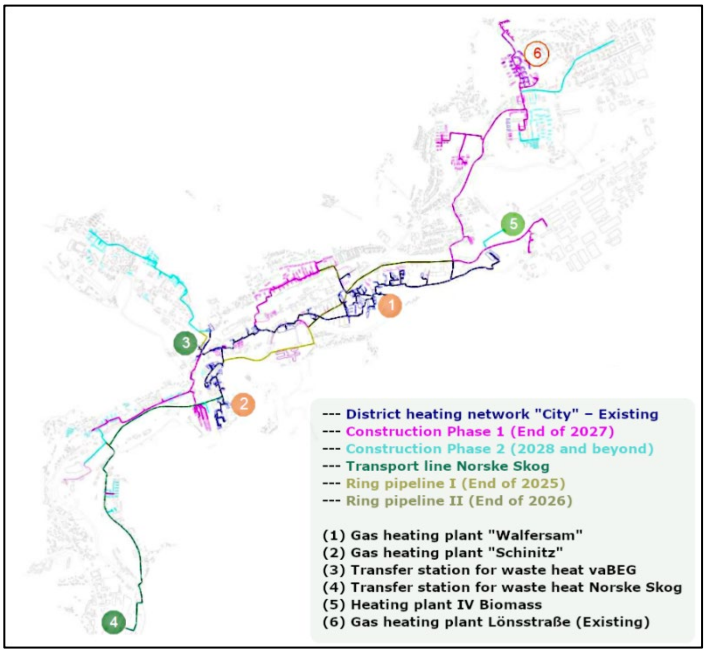

Figure 1. *Geographic system schematic of Kapfenberg DH system [6]*

2.1 Current System Configuration

The Kapfenberg DH system comprises one main network (Fernwärmenetz “Stadt”) and seven smaller micro-grids. The main network supplies 1,357 customers with a connected load of 16.1 MW and an annual heat demand of 19.96 GWh. The total network length is 8.7 km, operated at conventional temperature levels of approximately 90 – 95 °C supply and 60 °C return.

Heat production in the current configuration relies predominantly on fossil-based sources, with two natural gas boilers providing a combined thermal capacity of 9.4 MW and an annual output of approximately 20.4 GWh. Renewable contribution is currently limited to industrial waste heat supplied by the steel manufacturer Böhler, amounting to 4.7 MW of thermal capacity and around 3.1 GWh per year. One shall note that reported annual generation figures include auxiliary networks/losses and therefore exceed delivered heat of the main network.

2.2 Renewable Energy and Waste Heat Potentials

Several opportunities for expanding renewable and waste heat integration have been identified. These include additional industrial waste heat sources within Kapfenberg, the potential recovery of surplus heat from a paper mill in the neighbouring city of Bruck an der Mur, and an increase in waste heat utilisation from the Böhler steel plant. Furthermore, the local availability of woody biomass supports the option of installing a biomass combustion plant. Sector coupling options are also considered through the integration of a solar-based P2H unit, operated with on-site photovoltaic generation and, where economically viable, excess renewable electricity from the grid.

2.3 Project Scope

Within SUPPORT DHC, the expected outcomes include support for investment planning through comprehensive heat production planning based on energyPRO-driven operational optimisation of the plant portfolio. A techno-economic assessment of P2H operation is conducted, prioritising on-site PV electricity and grid electricity under defined price thresholds, with the objectives of reducing heat generation costs, increasing self-consumption, and limiting stress on the local electricity grid via price-responsive dispatch. These analyses are complemented by levelized cost of heat evaluations to quantify the economic impacts of alternative supply configurations.

Overall, the transformation of Kapfenberg's district heating system aims at an Energy Efficiency Directive–aligned, flexible, and low-emission configuration, capable of accommodating rising heat demand while enabling the efficient integration of low-grade renewable energy and waste heat sources.

Table 1. *Overview of the Kapfenberg district heating system boundary conditions, contrasting the current status quo with the long-term target configuration in terms of network extent, annual heat supply, and the envisioned transition from fossil-based generation toward a fully decarbonised portfolio centred on industrial waste heat and renewable sources.*

Notes	Status Quo	Long-Term Aim
Network Size	~9 km	~33 km
Annual Heat Supply	~20 GWh/a	~49 GWh/a
Supply	~80% gas, ~20% Waste Heat	Full Decarbonisation
Energy sources	Natural Gas, Waste heat from “voestalpine Böhler Edelstahl”	Waste Heat from Industry, Biomass, PV, RE-based Electricity from Grid

3. Methods

The methodological framework is designed to support integrated heat production planning for a transitioning district heating system. Rather than focusing on individual technologies in isolation, the approach evaluates the complete supply portfolio under realistic operational constraints.

3.1 Modelling Approach

The analysis is conducted using energyPRO, a commercially established energy system optimisation tool widely applied for techno-economic assessment of district heating systems. energyPRO enables detailed representation of multi-technology heat supply portfolios and performs cost-minimising dispatch optimisation based on user-defined operational constraints.

All simulations are carried out with hourly temporal resolution over a full reference year, allowing the model to capture seasonal variations, peak demand conditions, and interactions between supply technologies. The optimisation determines both dispatch schedules and, where applicable, capacity-related decision variables, ensuring consistency between operational behaviour and long-term planning objectives (dispatch is optimised hourly; P2H capacity is assessed parametrically over predefined range).

3.2 Demand Representation

Heat demand is represented by a validated hourly demand time series, reflecting the consumption characteristics of the Kapfenberg district heating network. The demand profile accounts for seasonal variability (*Figure 2*), including winter peak loads and transitional periods, and is consistent with the annual heat demand and connected load reported by the operator. To reflect the planned network expansion, demand development is implemented stepwise, assuming 50% of the expansion is realised in 2026, increasing to 75% in 2027 and reaching full implementation (100%) by 2028.

Peak demand conditions are explicitly preserved in the time series to ensure that capacity adequacy and backup requirements are correctly reflected in the optimisation results. This approach allows the assessment of supply-side flexibility options, including thermal storage and sector coupling technologies, under realistic load conditions.

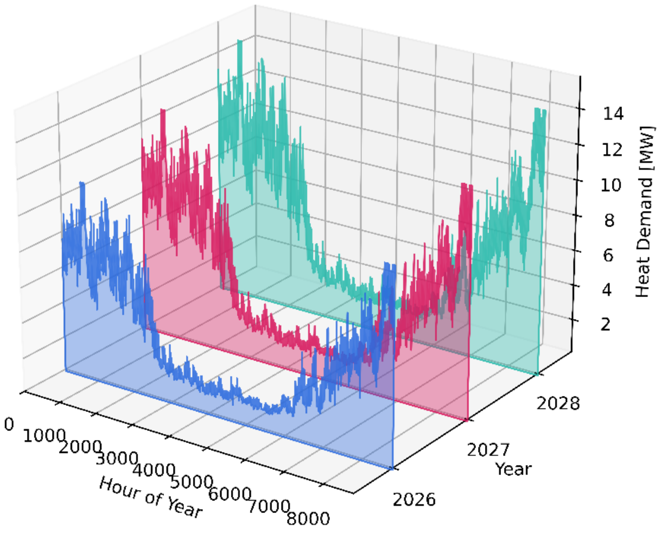

Figure 2. *Annual heat-demand profiles for the Kapfenberg case under the network-expansion scenario, shown separately for 2025 – 2027; each year representing hourly time series, enabling a direct comparison of seasonal demand dynamics.*

3.3 Supply Technologies and Constraints

The supply portfolio includes industrial waste heat, biomass boilers, natural gas boilers, and P2H units, each modelled with technology-specific efficiencies, availability patterns, and operational constraints. Availability windows and planned maintenance periods are implemented to reflect real operational practice. Where applicable, merit-order priorities defined by the operator are enforced or relaxed depending on the scenario.

Economic inputs include fuel costs, electricity prices, and operation and maintenance (O&M) costs, consistent with current and prospective market conditions. P2H is integrated as part of the overall heat planning framework, interacting with other supply technologies rather than being treated as a standalone solution. This ensures that optimisation outcomes reflect coherent system-wide transition pathways aligned with investment planning needs.

Table 2*. Supply technologies and operational constraints used in the energyPRO optimisation*

Plant	**Max / Min Capacity [MW_{th}]**	**Efficiency [%]**	**Type [-]**	**Priority [-]**	**Ramp Up / Down [min]**	**Uptime [-]**
Biomass Boiler	5 / 1.5	90%	Biomass	–	30 / 30	–
vaBEG[†] – Base	0.45 / 0.02	100%	Waste Heat	High	5 / 5	CSD[*]
vaBEG[†] – Max	6 / 0.3	100%	Waste Heat	High	5 / 5	CSD[*]
Norske Skog[‡]	10 / 0.5	100%	Waste Heat	High	5 / 5	–
P2H[§] unit	1 / 0.1 Nom	100%	Electricity	High	–	–
NG[‖] Back-Up	5 / 0.5	85%	NG	–	5 / 5	–

[*] CSD: Controlled Shut Down at weekends and annual maintenance in January and July.
[†] vaBEG: shorthand for voestalpine BÖHLER Edelstahl GmbH & Co KG.
[‡] Norske Skog: refers to Norske Skog Bruck GmbH (paper mill) located in Bruck an der Mur, Austria.
[§] P2H: refers to Power-to-Heat unit.
[‖] NG: refers to Natural Gas.

3.4 Economic Assessment

The economic assessment follows the annuity method of VDI 2067 [7], which converts one-off payments (investments and replacements) and ongoing payments (e.g., energy, operation and maintenance) over an observation period T into equivalent annual costs. These annualized costs are subsequently normalized by the annual useful heat supplied to obtain the Levelized Cost of Heat (LCOH).

For each installation component j with initial investment $A_{0,j}$ and service life $T_{N,j}$, the annuity of capital-related costs is computed as:

$$AN_{K,j} = \left(A_{0,j} + \sum_{i=1}^{n_j} A_{i,j} - RW_j \right) \tag{1}$$

where $A_{i,j}$ denotes the present value of the i-th replacement procured within T, RW_j the residual value at the end of T discounted to year 0, and a the annuity factor.

Replacement cash values are derived by escalating the investment with a price change factor r and discounting with the interest factor q:

$$A_{i,j} = A_{0,j} \frac{r^{iT_{N,j}}}{q^{iT_{N,j}}} \qquad i = 1, \dots, n_j \tag{2}$$

VDI 2067 determines the residual value by straight-line depreciation up to the end of the observation period and discounting to the beginning of that period. Importantly, if $T > T_{N,j}$ (i.e., replacements occur), depreciation is applied to the replacement investment rather than the initial investment.

Using the VDI 2067 formulation, residual value can be expressed compactly as:

$$RW_j = A_{0,j} r^{n_j T_{N,j}} \left(\frac{(n_j + 1) T_{N,j} - T}{T_{N,j}} \right) \frac{1}{q^T} \tag{3}$$

where n_j is the number of replacements within T.

The annuity factor is given by:

$$a = \frac{q^T (q-1)}{q^T - 1} \tag{4}$$

VDI 2067 groups ongoing costs into demand-related, operation-related, and other costs, which can be annualised via price-dynamic cash value factors b (potentially distinct for each cost category).

For demand-related costs (e.g., fuel and electricity), the annuity is formulated as:

$$AN_V = AV_1 a\, b_v \tag{5}$$

where AV_1 is the first-year demand-related cost. Analogous formulations apply for operation-related and other costs.

The price-dynamic cash value factor is derived as:

$$b = \frac{1 - \left(\frac{r}{q}\right)^T}{q - r}, \quad and\, for\, r = q \colon b = \frac{T}{q} \tag{6}$$

The equivalent annual cost of the system is obtained by summing the annuities of the cost categories:

$$AN_{tot} = \sum_{j} AN_{K,j} + AN_V + AN_B + AN_S \tag{7}$$

where AN_B and AN_S represent operation-related and other costs, respectively.

Finally, the levelized cost of heat is calculated by normalising the annualised cost by the annual net useful heat supplied Q_{heat}:

$$LCOH = AN_{tot}/Q_{heat} \tag{8}$$

In line with VDI 2067, proceeds can be treated analogously and netted against annual costs if required (e.g., for profitability assessments). However, for a cost-of-heat indicator, the present work reports LCOH on a cost basis using the annualised cost components and the simulated annual heat delivery.

4. Scenario Definition

The scenario set is designed to support supply-side optimisation and transition planning for the Kapfenberg district heating system under realistic operational constraints, consistent with the SUPPORT DHC objective. In this paper, the scenario design primarily serves to (i) establish a robust reference portfolio for the planned system configuration and (ii) quantify the techno-economic value of Power-to-Heat (P2H) as a flexibility option within the supply portfolio.

4.1 Reference System

A reference scenario is defined to represent the operator’s transition-oriented plant portfolio and operating practice, including the planned waste-heat integrations, biomass capacity, and thermal storage, subject to the availability constraints and technical limits described in Section 3.3. Operator-defined technology priority constraints (i.e., preferential utilisation of waste heat when available) are applied in this reference configuration and retained for all subsequent P2H scenarios to ensure consistent benchmarking.

4.2 PV-Only P2H Scenario

In the PV-only scenario, a P2H unit is added to the reference portfolio, with electricity supply constrained to on-site PV generation. Following operator-provided boundary conditions, the installed PV capacity is fixed at 100 kW, and the P2H capacity is evaluated parametrically at 50, 100, 200, and 300 kW. For each candidate P2H size, hourly dispatch is optimised in energyPRO subject to the same technical limits and availability constraints as in the reference configuration. This formulation quantifies the achievable contribution of P2H when operation is strictly limited to locally available PV electricity and therefore reflects a conservative sector-coupling configuration.

4.3 Grid-Enabled P2H Scenario

The grid-enabled scenario extends the PV-only formulation by permitting electricity imports from the grid under a price-threshold operating rule. The PV capacity remains fixed at 100 kW, while the P2H capacity is assessed over 300, 1,000, 2,000, 3,500, and 5,000 kW. Hourly operation is optimised using the day-ahead electricity price time series as an exogenous signal for grid electricity procurement.

Specifically, grid electricity intake for P2H is allowed only in hours when the day-ahead price is at or below a predefined threshold otherwise the P2H unit may operate only on on-site

PV generation (if available). The threshold thus represents an operator-side purchasing criterion for economically favourable electricity hours and serves as a practical proxy for periods that often coincide with high renewable generation in the power system (low marginal prices), without modelling any electricity-market feedback. Threshold values of 20, 40, 60, and 80 €/MWh are applied to span conservative to permissive import conditions.

For each combination of P2H capacity and threshold, energyPRO optimises the hourly dispatch of the full heat supply portfolio subject to the technical constraints and availability assumptions defined in Section 3.3. This formulation allows identification of cost-effective P2H sizing and operating regimes and supports supply-side transition planning by explicitly linking P2H utilisation potential to the frequency and duration of low-price operating windows.

5. Results

5.1 PV-Only P2H Operation

Figure 3 summarises the PV-only scenario outcomes in terms of annual P2H heat delivery and the resulting LCOH. Relative to the reference case without P2H (LCOH 110.053 €/MWh), introducing P2H under PV-only operation yields a modest cost reduction across the evaluated capacities. The minimum LCOH is observed at 100 kW P2H with 109.867 €/MWh, while 200 kW results in a nearly identical value (109.870 €/MWh). At 50 kW, LCOH decreases to 109.929 €/MWh, whereas at 300 kW it increases slightly to 109.915 €/MWh, indicating diminishing marginal benefit at higher P2H capacities under the imposed PV constraint.

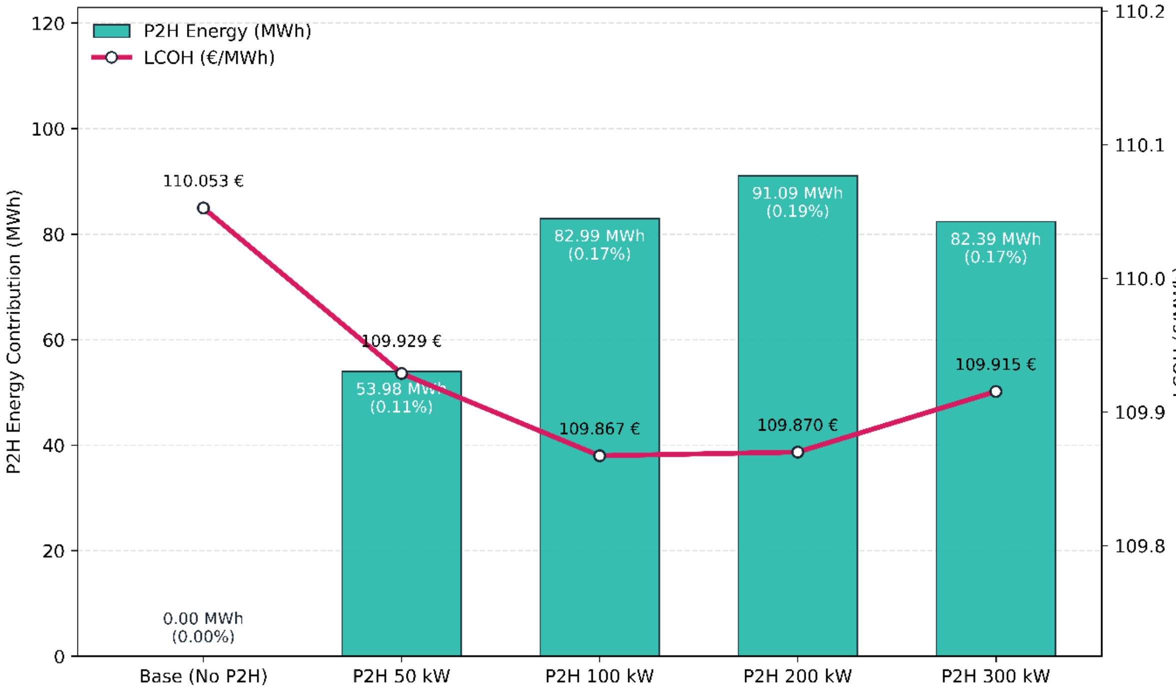

Figure 3. *PV-only P2H scenario results for Kapfenberg (on-site PV capacity: 100 kW): annual P2H heat delivery (bars, with share of total heat demand) and corresponding LCOH (line) for candidate P2H capacities of 50–300 kW, benchmarked against the reference case without P2H.*

The annual P2H energy contribution remains small in all PV-only cases, amounting to 53.98 MWh (0.11%) for 50 kW, 82.99 MWh (0.17%) for 100 kW, 91.09 MWh (0.19%) for 200 kW, and 82.39 MWh (0.17%) for 300 kW. The results show that, within the fixed PV capacity boundary, higher P2H capacities do not translate proportionally into higher annual utilisation.

5.2 Grid-Enabled P2H Operation

Figure 4 presents the LCOH response surface for the grid-enabled P2H scenario as a function of installed P2H capacity and the electricity purchase price threshold. A clear cost-minimising region is identified around 2,000 kW P2H capacity and a threshold of approximately 40 €/MWh, where the lowest contour level is about 109.56 €/MWh.

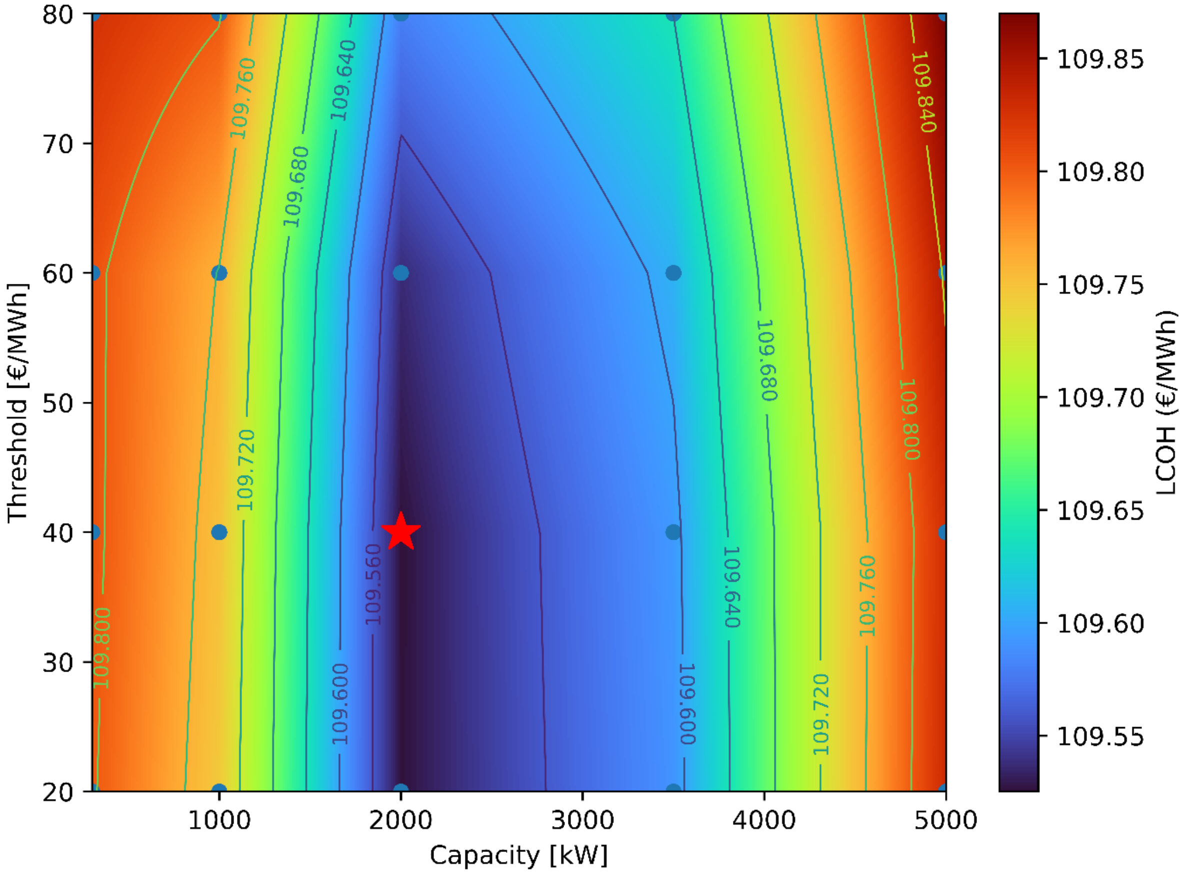

Figure 4. *Grid-enabled P2H scenario results for Kapfenberg (on-site PV capacity: 100 kW): LCOH contour map as a function of installed P2H capacity (0.3–5 MW) and electricity price import threshold (20–80 €/MWh), indicating the cost-minimising region (star) under price-responsive operation.*

Across the explored design space, LCOH increases for both (i) smaller P2H capacities below the identified cost-minimising range and (ii) larger capacities toward the upper bound of 5,000 kW, demonstrating diminishing returns once the economically attractive operating hours are exhausted under the applied threshold logic. The contour pattern further indicates that the vicinity of the minimum extends over a range of thresholds around the optimum, whereas threshold values at the upper end (towards 80 €/MWh) yield systematically higher LCOH levels across capacities.

6. Discussion

The Kapfenberg case demonstrates that portfolio-level, constraint-aware supply-side optimisation is a practical basis for transition planning in existing, high-temperature district heating systems. By representing technology availability, planned maintenance windows, minimum-load constraints, and operator-defined dispatch priorities, the optimisation provides an internally consistent assessment of how planned renewable heat and waste heat measures perform under realistic operating conditions, rather than under idealised assumptions. This is directly aligned with the SUPPORT DHC objective of enabling implementable transformation and investment plans for accelerated integration of low-grade renewable energy and waste heat in current networks.

Across the assessed configurations, the optimisation consistently indicates industrial waste heat as the dominant cost-optimal supply component. This outcome is primarily driven by its low marginal cost relative to fuel-based options. Importantly, the result should be interpreted as conditional on the assumed waste heat potentials, availability constraints (including controlled shutdown and annual maintenance), and the remaining portfolio composition.

The results indicate that the techno-economic value of P2H is highly dependent on boundary conditions and should be framed as a flexibility measure within integrated supply planning, rather than as a standalone decarbonisation solution. In the PV-only case, P2H contributes only a very small share of annual heat delivery and yields limited LCOH improvements, reflecting the restricted operating window imposed by the assumed on-site PV capacity and the temporal coincidence of PV availability with system needs. In this setting, increasing installed P2H capacity does not translate into proportional utilisation, because operation is constrained by electricity availability rather than by heat-side demand.

In contrast, the grid-enabled formulation reveals a clear optimum around medium-scale P2H capacities (~2 MW) under a moderate purchase-price threshold (~40 €/MWh). The shape of the LCOH surface indicates that the main benefit of P2H arises from accessing a limited set of economically attractive operating hours; beyond the optimum, marginal gains diminish as these hours saturate. This behaviour is consistent with a flexibility asset whose value is governed by (i) the frequency of low-price hours and (ii) competing low-marginal-cost heat supply options, particularly waste heat. As modelled here, the price-threshold rule should be interpreted as an operator-facing proxy for periods with favourable electricity conditions rather than as a representation of electricity market feedback.

From a planning perspective, the optimisation outcomes provide two directly actionable insights. First, prioritising and operationally securing industrial waste heat utilisation appears central for maintaining low heat costs while advancing decarbonisation, supporting an investment logic focused on heat recovery interfaces, interconnection capacity, and reliability measures. Second, P2H can be justified as a complementary flexibility option if its operation is anchored to clearly defined boundary conditions (e.g., price thresholds) and if its capacity is sized to avoid oversizing relative to the economically utilisable operating window. This helps avoid technology-led planning and instead supports package-oriented investment decisions, consistent with the SUPPORT DHC framing.

7. Conclusions

This paper presented an optimization-based heat production planning study for the district heating system of Stadtwärme Kapfenberg GmbH (Austria), conducted within the SUPPORT DHC framework to support EED-aligned transformation and investment planning towards full decarbonisation by 2040. Using an hourly energyPRO model with operator-specific boundary conditions (availability constraints, maintenance windows, minimum-load limits, and dispatch priority constraints), the analysis quantified cost-optimal supply portfolios for the current and planned expanded system configurations and assessed P2H as one flexibility option within the integrated supply portfolio.

The results indicate that, across the analysed scenarios and boundary conditions, industrial waste heat remains the dominant component of the cost-optimal portfolio, reinforcing its central role in the near- to mid-term transition pathway for high-temperature district heating networks. Under PV-only operation with the assumed on-site PV capacity, P2H contributes only marginally to annual heat supply and yields limited reductions in LCOH, demonstrating that the achievable benefit is strongly constrained by local renewable electricity availability. In contrast, enabling price-responsive grid electricity imports reveals a distinct optimum in the explored design space: minimum LCOH occurs at medium-scale P2H capacities around 2 MW under moderate price thresholds, while larger capacities show diminishing marginal benefits as economically attractive operating hours saturate.

From a planning perspective, the study demonstrates the value of supply-side optimisation as a decision-support instrument to (i) prioritise and operationalise low-grade renewable and waste heat integration measures and (ii) screen flexibility options such as P2H in a manner consistent with operator practice and investment planning needs.

Data availability statement

No new data were generated or analysed in this study; therefore, no data are available for public sharing.

Underlying and related material

No supplementary material or external datasets/software artefacts were deposited in a public repository for this contribution.

Author contributions

Conceptualization: SR, IL, and EW; Data Curation: HIT and SR; Formal Analysis: HIT and SR; Funding Acquisition: SR and IL; Investigation: HIT, SR, and IL; Methodology: HIT, SR, and IL; Project Administration: SR and IL; Resources: EW; Software: HIT and SR; Supervision: SR and IL; Validation: HIT and SR; Visualization: HIT and SR; Writing – Original Draft: HIT and SR; and Writing – Review & Editing: HIT and SR.

Competing interests

The authors declare that they have no competing interests.

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