Integration of Power-to-X Waste Heat into Hamburg's District Heating System: Energy Efficiency, CO_2 Reduction, and Operational Optimization

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***Abstract*—Power-to-X (PtX) can support sector coupling by converting renewable electricity into hydrogen and synthetic methane. A useful but often underused co-product is waste heat from electrolysis and methanation, which can be injected into district heating (DH) networks. This study analyzes a 100 MW PtX plant in Hamburg and quantifies its contribution to DH supply, CO_2 reduction, and operating economics. A transparent hour-by-hour Excel model is built using German day-ahead electricity prices for January–February 2024 (1440 hours) together with a realistic winter DH load profile. Two operating strategies are compared: a simple price-threshold rule (operate when price $<$ 100 €/MWh) and an economically optimized strategy based on a break-even electricity price of 39.3 €/MWh. Under the 100 €/MWh strategy, the plant supplies 89,561 MWh_{th} of heat (5.18% of DH demand) and avoids 17,733 t CO_2, but the net operating cost is 3.35 M€. Under the optimized strategy, heat supply falls to 11,300 MWh_{th} and CO_2 savings to 2,237 t, while the net result becomes a profit of 0.55 M€. The results show that PtX waste heat can meaningfully support DH decarbonization, but profitable operation requires flexible dispatch in response to electricity prices.**

***Index Terms*—Power-to-X, District Heating, Hydrogen, Methanation, Waste Heat Integration, Hamburg, CO_2 Reduction, Operational Optimization, Sector Coupling.**

I. Introduction

A. Background and Motivation

Europe's transition toward climate neutrality requires deep integration of fluctuating renewable energy sources such as wind and solar power. As the share of variable renewable energy increases, it becomes more difficult to balance generation and demand using only traditional flexibility options. Sector coupling is increasingly important for balancing the power system and reducing emissions in heating, transport, and industry. In particular, the heating sector remains a major contributor to final energy consumption and CO_2 emissions in many urban areas, and decarbonizing heat supply is therefore essential for achieving climate targets.

Power-to-X (PtX) technologies enable this sector coupling by converting surplus renewable electricity into green hydrogen or synthetic methane (SNG). Hydrogen can be used as an industrial feedstock, in mobility, or as a direct fuel, while SNG can be injected into existing gas grids and used in boilers, CHP units, or industrial processes. System-level assessments emphasize that hydrogen can support long-term energy storage and flexibility in future low-carbon energy systems [5], [6]. However, the PtX conversion chain also produces substantial amounts of recoverable waste heat—often representing more than 20–35% of the total input electricity [2], [4]. If this heat is rejected to the ambient, the overall system efficiency of PtX installations remains modest.

In contrast, when waste heat is integrated into district heating (DH) networks, both the PtX facility and the DH system benefit: the PtX plant increases its useful output, while the DH network can reduce its consumption of fossil fuels and associated CO_2 emissions. This is especially relevant for cities with established DH infrastructure, where waste heat integration can be a practical decarbonization measure alongside other low-carbon sources such as heat pumps, biomass, geothermal energy, and industrial excess heat.

B. Why Hamburg?

Hamburg is an especially attractive location for PtX–DH integration due to a combination of technical, geographical, and infrastructural factors:

- A large DH network with an annual demand exceeding 5.3 TWh, which provides a substantial and continuous heat sink for industrial waste heat [3], [7].
- An ongoing transition away from coal-based heat sources and an explicit political goal to decarbonize heat supply, as described in the city's DH roadmap [3].
- Proximity to offshore wind resources and north German onshore wind, which provides frequent periods of low or even negative electricity prices that can be exploited by flexible PtX plants.
- Major industrial clusters and point sources of CO_2 in the port and industrial areas, which can supply the carbon needed for methanation.
- Planned large-scale hydrogen and PtX projects in the port area, making it realistic that an electrolyser and methanation plant could be located close to existing DH transmission pipelines.

These factors make Hamburg well-suited for integrating PtX waste heat into its district heating system.

C. Literature and Research Gap

Previous studies emphasize the flexible operation of electrolyzers and their role in future energy systems. Emonts et al. [1] show that electrolyzers can provide demand-side flexibility by responding to dynamic electricity prices, thus supporting system balance. Götz et al. [2] provide a comprehensive technological and economic review of renewable Power-to-Gas systems, including discussion of efficiency, costs, and heat integration options. Buttler and Spliethoff [4] summarize the status of water electrolysis for energy storage, grid balancing, and sector coupling, highlighting that operational flexibility strongly affects economic outcomes. Broader system studies also underline hydrogen's strategic role in a decarbonized energy system [5], [6].

However, only limited work explicitly quantifies the direct integration of PtX waste heat into a specific DH system under real electricity-price dynamics. There is also a lack of detailed analysis of how different operational strategies influence both (i) the magnitude of waste heat supplied to DH and (ii) the net operating cost of the PtX plant. This paper addresses that gap for Hamburg by combining hourly simulation with two dispatch logics: a simple threshold and a stricter economic break-even threshold.

D. Objective and Scope

The objective of this study is therefore:

> **To quantify the energy efficiency improvement, CO_2 reduction, and economic trade-offs of integrating waste heat from a 100 MW PtX facility into Hamburg's district heating system, and to evaluate which operational strategy provides the highest benefit.**

The scope of the work is restricted to:

- a single 100 MW PEM electrolyser,
- a Sabatier methanation unit with heat recovery,
- an industrial heat pump upgrading low-temperature heat,
- a DH network represented by an aggregated hourly load curve,
- a winter period of 1440 hours (January–February 2024),
- operation based on day-ahead-price signals.

Investment costs, grid constraints, long-term storage, and detailed DH hydraulics are outside the scope but are discussed qualitatively in the Conclusions and Outlook. This boundary is chosen to keep the analysis transparent and to focus on the operational interaction between electricity prices, PtX dispatch, and DH heat recovery.

II. Methodology

A. System Overview

The model consists of three main components:

1) **100 MW PEM electrolyser:** converts electricity to hydrogen and produces low-grade heat.
2) **Sabatier methanation reactor:** converts H_2 and CO_2 to CH_4 and releases high-temperature reaction heat.
3) **Heat pump (HP):** upgrades electrolyser heat to a temperature suitable for DH supply, with a coefficient of performance (COP) of 3.

All waste heat is assumed to be delivered directly into Hamburg's DH network. This is a simplification but is reasonable as a first-order approach, since Hamburg already has experience in connecting industrial waste-heat sources to DH pipelines and identifies waste heat as a key supply option [3], [7]. The PtX plant is assumed to be sited in the port area close to existing DH infrastructure, limiting heat transport distance and therefore distribution losses.

A key modelling assumption is that no thermal storage is included. Storage could increase the amount of waste heat that can be used by decoupling PtX operation from instantaneous DH demand, but it would also introduce additional complexity and cost. Excluding storage keeps the modelling conservative: recovered heat can only be credited if DH demand exists at the same time. In practice, short-term thermal storage (e.g., hot water tanks) is common in DH systems and would likely improve heat utilization.

B. Mathematical Model of Energy Flows

Electrolyser operation is controlled by a dimensionless variable $u(t) \in [0, 1]$, representing the fraction of rated capacity used in hour t. In this project, only full-load and zero-load operation are considered (0 or 1), but the formulation is general:

$$P_{el}(t) = 100 \cdot u(t).$$

The hydrogen production in each hour is given by:

$$E_{H_2}(t) = P_{el}(t)\eta_{el},$$

where the electrolyser efficiency is $\eta_{el} = 0.68$, in line with values reported in [1], [2], [4]. The methane production is then:

$$E_{CH_4}(t) = E_{H_2}(t)\eta_{meth},$$

with $\eta_{meth} = 0.78$, representing the lower heating-value efficiency from hydrogen to methane.

The electrolyser waste heat is calculated as:

$$Q_{el}(t) = P_{el}(t)(1 - \eta_{el}),$$

which approximates the difference between electric input and chemical output. Methanation heat is given by:

$$Q_{meth}(t) = 0.72\, E_{CH_4}(t),$$

based on typical values for Sabatier reactors where 0.7–0.8 MWh_{th} of heat is released per MWh of methane produced [2]. The total recoverable PtX heat before any storage is therefore:

$$Q_{PtX}(t) = Q_{el}(t) + Q_{meth}(t).$$

In reality, only part of the electrolyser heat is at a suitable temperature level, so a heat pump is used. The COP is included in the economic model (electricity input to the heat pump), while the energy model focuses on the final delivered heat to DH. This separation keeps the energy accounting clear while still representing the cost penalty of temperature upgrading. This approach is consistent with the literature view that electrolysis-based systems can provide both chemical energy and useful heat when coupled to urban heat demand [4], [5].

C. District Heating and CO_2 Model

The DH load is represented by a sinusoidal winter pattern with hourly variations between 900 MW_{th} and 1500 MW_{th}. This shape reflects typical winter daily load patterns in Hamburg with higher demand in the morning and evening, and lower demand at night, consistent with the profiles presented in [3].

In each hour, PtX heat is dispatched first. Any remaining demand is covered by gas boilers:

$$Q_{gas}(t) = \max(Q_{DH}(t) - Q_{PtX}(t), 0).$$

This means that PtX heat always displaces gas heat one-to-one within the simplified system boundary. The CO_2 reduction is calculated from the amount of displaced gas heat using an emission factor of 0.198 t/MWh_{th}, which is representative of modern natural-gas boilers:

$$\Delta CO_2(t) = 0.198 \cdot Q_{PtX}(t).$$

Aggregating over all hours gives the total CO_2 reduction achieved by PtX waste-heat integration. Although simplified, this method provides a transparent estimate of heat-sector abatement, consistent with many first-order DH decarbonization assessments.

D. Economic Framework

The economic analysis considers the variable operating costs and revenues:

- Electricity cost for the electrolyser and heat pump.
- Revenue from selling methane.
- No direct revenue is assigned to heat, consistent with a conservative assumption where the PtX operator is not paid for DH heat.

The hourly net cost is:

$$C(t) = p(t) \left(P_{el}(t) + P_{HP}(t)\right) - p_{CH_4} E_{CH_4}(t),$$

where $p(t)$ is the day-ahead electricity price, $P_{HP}(t)$ is the heat pump power, and p_{CH_4} is the methane sales price, set to 80 €/MWh. The total net cost over the simulated period is obtained by summing $C(t)$ over all 1440 hours.

Two operational strategies are evaluated:

- **Simple threshold:** $u(t) = 1$ if $p(t) < 100\ /MWh$, otherwise $u(t) = 0$. This represents a heuristic rule that is easy to understand and implement.
- **Optimized strategy:** an analytically derived threshold $p_{crit} = 39.3\ /MWh$, where the marginal electricity cost equals the marginal methane revenue. Only hours with $p(t) < p_{crit}$ are profitable, so the electrolyser is operated in those hours only.

This comparison directly illustrates the trade-off between maximizing heat/CO_2 benefits and maximizing private economic performance, which is frequently emphasized in hydrogen policy discussions [5], [6].

III. Data

Real German day-ahead electricity prices from the ENTSO-E transparency platform for January–February 2024 (1440 hours) were used as the main driving signal for PtX operation. Using actual market prices is critical because PtX profitability depends strongly on the frequency and duration of low-price periods, which are influenced by renewable output, demand, and interconnector flows.

Technical parameters such as electrolyser efficiency, methanation efficiency, and heat recovery fractions were selected based on the ranges reported in [1], [2], [4]. The chosen values are representative of near-future PtX plants rather than idealized high-efficiency systems, and they provide a realistic basis for assessing both heat recovery and the economic implications of electricity consumption.

The DH load profile is synthetic but constructed to be consistent with Hamburg's heat demand as described in [3], [7]. The absolute scale (900–1500 MW_{th}) and daily fluctuations are chosen to match typical winter conditions. This ensures that the analysis captures the operational context in which recovered heat would actually be utilized.

All hourly calculations were implemented in Excel in two separate files. The first file, `PtX_Energy_calculations_2months.xlsx`, contains the energy and CO_2 calculations, while the second file, `PtX_Optimization_2months.xlsx`, implements the economic model and operational optimization.

IV. Results

A. Electricity Price and DH Load

Fig. 1 shows winter price volatility, including low and high-price periods. Fig. 2 shows the DH load variation.

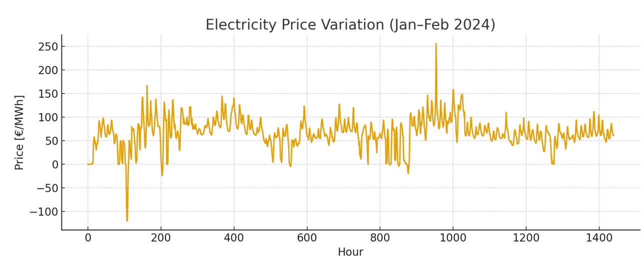

Fig. 1. Electricity price variation (Jan–Feb 2024).

The electricity price time series demonstrates several distinct regimes: extended periods with moderate prices (50–100 €/MWh), short episodes of very high prices above 200 €/MWh, and occasional low-price or near-zero hours. These regimes are critical for PtX economics because they determine when electricity can be profitably converted to hydrogen and methane. The DH load profile is comparatively

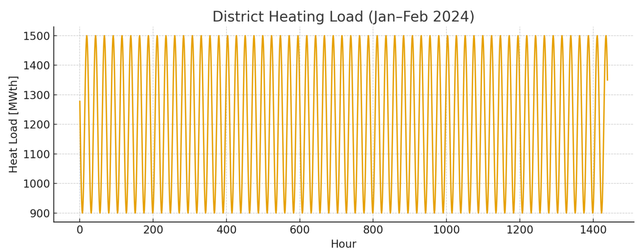

Fig. 2. District heating load for winter period.

smooth, with daily peaks in the morning and evening. This mismatch in variability supports the broader argument that electrolysers can act as flexible loads that follow renewable generation availability [1], [4].

B. Base Case Summary (100 €/MWh Threshold)

In the base case, the electrolyser is operated whenever the electricity price is below 100 €/MWh. This leads to many operating hours and therefore large hydrogen/methane production and large waste heat generation. The aggregated results are summarized in Table I.

TABLE I
BASE CASE SUMMARY

Hours ON	1276
PtX Heat	89,561 MWh_{th}
DH Share	5.18%
CO_2 Avoided	17,733 t
Net Cost	3.35 M€

The PtX facility delivers 89,561 MWh_{th} of heat to the DH network over the two-month period, covering 5.18% of the total DH demand. This reduces gas boiler consumption accordingly and leads to a CO_2 reduction of 17,733 t. From a heat-sector perspective, this is a substantial seasonal contribution. However, the net operating cost is positive (3.35 M€), meaning that under this dispatch logic the plant loses money due to operation in hours where electricity prices are not sufficiently low relative to methane revenues.

C. Optimized Strategy Summary (39.3 €/MWh)

For the optimized strategy, the plant operates only when the electricity price is below the break-even threshold of 39.3 €/MWh. This strongly reduces operating hours and therefore reduces delivered heat and avoided emissions. The aggregated results are shown in Table II.

TABLE II
OPTIMIZED SUMMARY

Hours ON	161
PtX Heat	11,300 MWh_{th}
DH Share	0.65%
CO_2 Avoided	2,237 t
Net Cost	–0.55 M€

Although the DH share and CO_2 savings are much lower than in the base case, the optimized strategy yields a slightly negative net cost (i.e., a profit) of 0.55 M€. This outcome is consistent with the economic principle that electricity-intensive hydrogen production is most favorable during low-price periods [5], [6]. The results therefore illustrate that operational optimization shifts the PtX plant from a decarbonization-first operation toward a profitability-first operation.

V. DISCUSSION

A. Energy Efficiency Improvements

When waste heat is recovered, PtX overall efficiency increases substantially. Without heat recovery, the system efficiency is limited to the hydrogen/methane conversion efficiency (on the order of 53–68%). With heat integration into DH, total useful energy—in the form of fuels plus heat—exceeds 80%. This demonstrates that PtX becomes significantly more cost- and energy-efficient when waste heat is captured and that DH integration is an attractive way of improving the effective utilization of electricity in PtX systems. The literature similarly emphasizes that coupling electrolysis with heat utilization can significantly increase the fraction of input electricity converted into useful outputs [4], [5].

B. Operational Strategy Implications

The base-case strategy maximizes heat output and CO_2 reduction but incurs financial losses due to high electricity costs in many of the operating hours. This reflects a situation where PtX is primarily operated as a decarbonization tool, without explicit regard for profitability. In practice, such operation might require policy support, such as subsidies, contracts for difference, or explicit payments for recovered heat.

Conversely, the optimized strategy prioritizes electricity arbitrage and fuel sales. It results in much fewer operating hours, but the hours used are economically favourable, resulting in a modest profit. From a private investor's standpoint, such a strategy is more realistic and aligns with energy-system studies discussing hydrogen deployment pathways and market design [5], [6]. However, this strategy significantly reduces the decarbonization benefit for the DH system. The results therefore highlight that the preferred strategy depends on whether the objective is maximum CO_2 reduction or minimum cost (or profit).

C. Infrastructure Readiness

Hamburg's DH pipelines, existing CHP plants, industrial clusters, and planned hydrogen infrastructure make the city particularly suitable for PtX integration. The main additional infrastructure required would be:

- heat exchangers and connection pipes between the PtX plant and the DH grid,
- potential booster pumps or local temperature control equipment,
- CO_2 capture units or pipeline connections to existing CO_2 sources.

No fundamental technical barriers are apparent, and Hamburg's DH planning documents emphasize the role of waste heat [3], [7], suggesting that PtX waste heat would fit into ongoing planning. In addition, siting PtX facilities close to large heat sinks is a practical systems-integration strategy because it reduces thermal losses and connection cost.

D. Limitations and Future Work

The model developed for this project is intentionally simplified:

- only a winter period was considered; annual operation may show different economics and heat shares,
- no thermal storage or DH network constraints were included,
- start-up costs, ramp-rate limitations, and part-load efficiency curves were neglected,
- the methane and gas prices were assumed constant.

Future work should extend the analysis to a full year, incorporate large-scale thermal storage, and apply mixed-integer linear programming (MILP) to capture start-up costs and binary on/off decisions explicitly. Additionally, combining PtX waste heat with other low-temperature sources (data centres, industrial processes) could further increase the DH share served by low-carbon heat. More detailed analysis could also evaluate alternative revenue models, such as heat sales contracts or system-level valuation of flexibility, which are often highlighted as critical for scaling hydrogen technologies [4], [6].

VI. Conclusion

This study demonstrates that a 100 MW PtX facility located in Hamburg can significantly contribute to DH decarbonization and improve system efficiency. Under a 100 €/MWh threshold, the plant provides 89,561 MWh_{th} of heat and avoids 17,733 t CO_2 in just two winter months, covering 5.18% of the DH demand in the period. The optimised strategy highlights that PtX can operate profitably under favourable market conditions, although heat output and CO_2 savings are reduced.

The "best" configuration depends on whether the priority is climate impact (100 €/MWh case) or economic feasibility (39.3 €/MWh case). In both scenarios, PtX waste heat represents a valuable addition to Hamburg's long-term heat-transition strategy and illustrates how sector coupling can unlock additional benefits from renewable electricity. The modelling approach and results also satisfy the requirements for hourly energy-system calculations, explicit PtX technology description, and discussion of operation strategy, infrastructure, and environmental impacts.

Appendix: Calculation Files

Two Excel calculation files are submitted with this report:

- **PtX_Energy_Calculations_2months.xlsx** – Hourly energy and CO_2 model, including price series, PtX operation, PtX heat, gas heat, and avoided CO_2.
- **PtX_Optimization_2months.xlsx** – Economic and optimization model, including electricity costs, methane revenues, net cost, and implementation of the optimized price threshold.

TABLE III
SYMBOLS AND ABBREVIATIONS

PtX	Power-to-X conversion system
DH	District Heating network
HP	Heat Pump
SNG	Synthetic Natural Gas
$u(t)$	Electrolyser operating state
P_{el}	Electrolyser power input
E_{H_2}	Hydrogen energy produced
E_{CH_4}	Methane energy produced
Q_{PtX}	PtX total waste heat recovered
Q_{gas}	Gas boiler heat
COP	Heat pump coefficient of performance
CO_2 EF	Gas boiler emission factor

GAI Declaration

I hereby declare that I have used all known GAI tools for all parts of this project.

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