A FRAMEWORK FOR FLEXIBILITY ASSESSMENT OF DISTRICT HEATING AND COOLING SYSTEMS

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Content

The large-scale integration of variable renewable energy sources increases volatility in electricity markets [1] [2], creating incentives for energy actors to unlock flexibility potential across different energy carriers [3]. District heating and cooling (DHC) systems are well-positioned to provide flexibility to the power system through their increasing electrification.

However, actual flexibility provision from DHC systems remains limited compared to their technical potential [4]. A key reason for this gap is the lack of understanding regarding what kind of flexibility DHC systems can actually provide to the power system [5]. While existing research focuses on technical modeling [6] [7] or case-specific simulations [8] [9] [10], a consistent methodology to quantify and compare DHC flexibility across different contexts is lacking. This knowledge gap limits both scientific understanding and stakeholder decision-making.

This study addresses this challenge by developing a novel, comprehensive KPI-based framework for systematic quantification of DHC flexibility. The framework integrates multiple flexibility indicators with economic and environmental performance metrics, enabling holistic assessment beyond isolated technical analyses. It is applied to a case study of the planned DHC network in the Nyhavna district of Trondheim, Norway (2025-2040) to demonstrate its applicability for energy system flexibility assessments.

Method

The developed KPI framework combines energy system modeling with a structured evaluation methodology. The quantitative foundation is provided by the District Energy Stochastic Portfolio Optimization Model (DESPO), a two-stage stochastic mixed-integer linear program. This model determines the cost-optimal supply portfolio for DHC systems while accounting for uncertainties in energy prices, demand patterns, and policy conditions.

The KPI framework comprises multiple flexibility indicators, of which four core metrics are highlighted here: The Electricity Consumption Response (ECR) measures the relative change in total electricity consumption when responding to price signals. This metric is derived by comparing two separate optimization runs: one with time-varying electricity prices reflecting real market conditions, and one with constant prices at the annual average. The difference in total electricity consumption between these runs reveals the system's price-responsive flexibility, with negative values indicating strategic consumption reduction through load shifting away from high-price periods. The Operational Flexibility Range (OFR) visualizes the operational envelope through normalized representation of electricity consumption and thermal supply across all scenarios and years. Each point in Figure 1 represents one scenario-year combination, and the convex hull enclosing these points quantifies the system's operational adaptability. Larger areas indicate the system can operate across a wider range of operational states, demonstrating greater flexibility. Two storage-related metrics characterize temporal flexibility: The Storage to Peak Ratio (SPR) indicates the number of hours of theoretical peak coverage by relating installed storage capacity to peak thermal demand, while the Thermal Storage Utilization Factor (TSUF) quantifies charging and discharging activity relative to the maximum possible throughput.

These flexibility indicators are complemented by economic and environmental performance metrics, including the Levelized Cost of Thermal Energy (LCOT), Electrification Share (ES), and Thermal Carbon Intensity (TCI).

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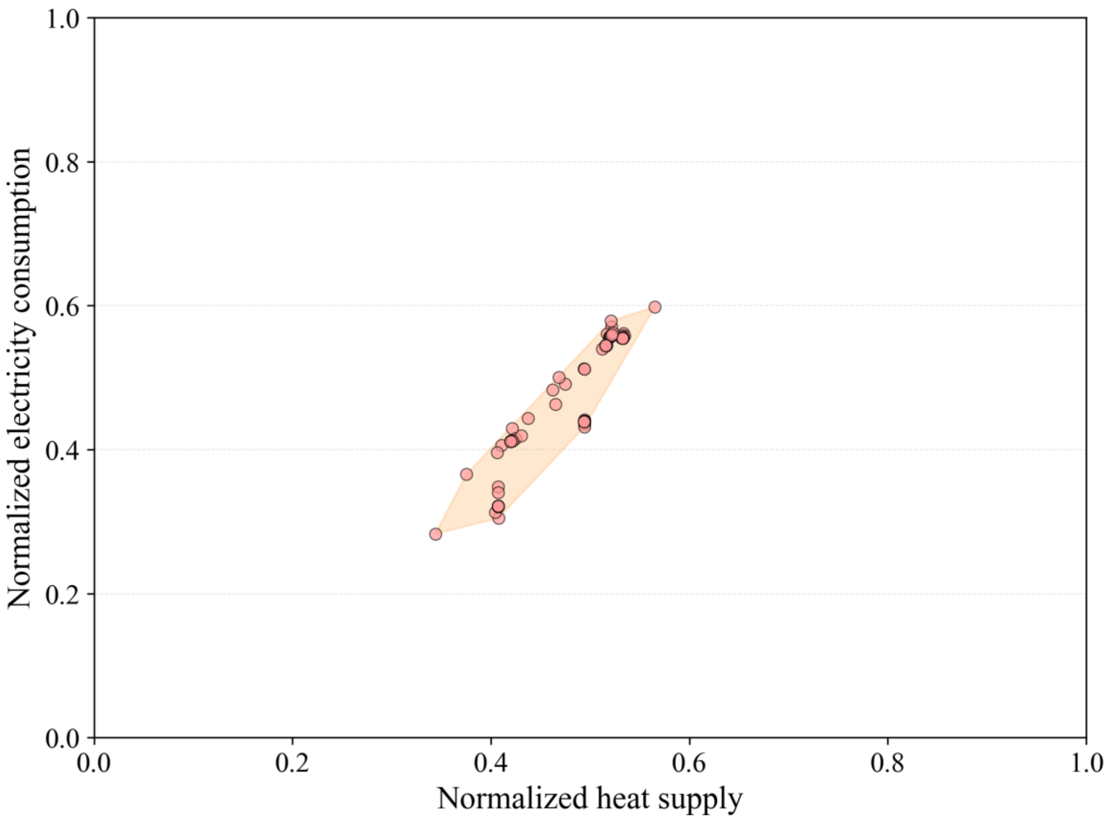

Figure 1: Operational Flexibility Range for the heating system. The normalized representation of electricity consumption vs. heat supply from electrified technologies visualizes the operational envelope. The area of the convex hull quantifies the flexibility potential.

Preliminary results

The analysis reveals distinct flexibility characteristics across heating and cooling subsystems. The heating system demonstrates operational flexibility with an ECR of -14.35 % in 2030, meaning the system reduces its electricity consumption through strategic load shifting away from high-price periods, providing significant grid balancing services.

The OFR of 1.4×10^{-2} quantifies the area of the convex hull in Figure 1 and confirms substantial operational adaptability across different operating conditions. Thermal storage indicators demonstrate active utilization for temporal load shifting, with an SPR of 2.87 h indicating the storage can theoretically cover nearly 3 hours of peak demand, and a TSUF of 39.50 % showing moderate storage activity with potential for increased flexibility provision. In contrast, the cooling system exhibits negligible flexibility due to minimal demand in Norway's climate.

Temporal evolution from 2025 to 2040 shows significant system transformation: the SPR triples from 2.87 h to 9.58 h, enabling extended temporal decoupling of supply and demand, while ES rises above 95 % and TCI decreases by more than 75 %. These trends position the system for enhanced grid service provision alongside progressive decarbonization.

Cross-scenario comparison reveals high structural stability in operational characteristics, with flexibility provision primarily determined by technology portfolio design rather than external conditions. Economic indicators show greater sensitivity, with LCOT varying between 32.31 €/MWh and 37.29 €/MWh across policy scenarios, demonstrating the substantial influence of regulatory frameworks on system economics.

The framework enables transparent, systematic quantification of DHC flexibility for decision-making in system integration and regulatory design.

Bibliography

[1] R. Wiser, A. Mills, J. Seel, T. Levin und A. Botterud, „Impacts of Variable Renewable Energy on Bulk Power System Assets, Pricing, and Costs," Lawrence Berkeley National Laboratory, 2017.

[2] P. Pereira da Silva und P. Horta, „The effect of variable renewable energy sources on electricity price volatility: the case of the Iberian market," *International Journal of Sustainable Energy,* Bd. 38, Nr. 8, pp. 794-813, 2019.

[3] J. Gorenstein Dedecca, M. Ansarin, C. Bene, T. van Delzen , L. van Nuffel und H. Jagtenberg, „Increasing Flexibility in the EU Energy System - Technologies and policies to enable the integration of renewable electricity source," European Parliament, Luxembourg, 2025.

[4] H. Golmohamadi, K. G. Larsen, P. G. Jensen und I. R. Hasrat, „Integration of flexibility potentials of district heating systems into electricity markets: A review," *Renewable and Sustainable Energy Reviews,* Bd. 159, 2022.

[5] K. M. Luc, A. Heller und C. Rode, „Energy demand flexibility in buildings and district heating systems – a literature review," *Advances in Building Energy Research,* Bd. 13, Nr. 2, pp. 241-263, 2019.

[6] A. Bloess, W.-P. Schill und A. Zerrahn, „Power-to-heat for renewable energy integration: A review of technologies, modeling approaches, and flexibility potentials," *Applied Energy,* Bd. 212, pp. 1611-1626, 2018.

[7] N. Blaauwbroek, P. H. Nguyen, M. J. Konsman, H. Shi, R. I. G. Kamphuis und W. L. Kling, „Decentralized Resource Allocation and Load Scheduling for Multicommodity Smart Energy Systems," *IEEE Transactions on Sustainable Energy,* Bd. 6, Nr. 4, pp. 1506-1514, 2015.

[8] H. Lund, B. Möller, B. V. Mathiesen und A. Dyrelund, „The role of district heating in future renewable energy systems," *Energy,* Bd. 35, Nr. 3, pp. 1381-1390, 2010.

[9] M. Münster, P. E. Morthorst, H. V. Larsen, L. Bregnbaek, J. Werling , H. H. Lindboe und H. Ravn, „The role of district heating in the future Danish energy system," *Energy,* Bd. 48, Nr. 1, pp. 47-55, 2012.

[10] K. Askeland, K. N. Bozhkova und P. Sorknaes, „Balancing Europe: Can district heating affect the flexibility potential of Norwegian hydropower resources?," *Renewable Energy,* Bd. 141, pp. 646-656, 2019.