

Quantifying the Flexibility Potential of District Heating and Cooling Systems: A KPI-Based Methodological Framework

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Motivation

- Increasing renewable energy integration creates electricity market volatility and drives demand for system flexibility. [1, 2]
- District heating and cooling (DHC) systems are well-positioned to provide grid flexibility through electrification (heat pumps, electric boilers). [3]
- However, actual flexibility provision remains limited compared to technical potential – DHC systems are traditionally viewed as heat suppliers, not as active grid participants. [4, 5]
- Key barrier: Lack of systematic methodology to quantify, compare, and benchmark DHC flexibility across different contexts. [6]

Research Questions and Objective

Research Questions:

- RQ1: How can a quantitative framework be designed to systematically assess and compare the flexibility potential of DHC systems?
- RQ2: What flexibility potential does the framework reveal for DHC systems across temporal horizons and varying scenarios, and which system characteristics prove robust versus sensitive to external conditions?

Aim and Core Objective:

- Develop a quantitative KPI framework to systematically assess DHC flexibility and support decision-making in integrated multi-energy systems.
- Demonstrate the framework's transferability and applicability through a Norwegian case study (Trondheim, 2025–2040).

Scope and Application

Modeling Framework:

- **GENeSYS-MOD^[7]**: Global energy system model; derived hourly electricity prices for Norway from decarbonization pathways.
- **DESPO^[8]**: Two-stage stochastic optimization determines cost-optimal DHC technology portfolio under uncertainty (policy variations, price fluctuations, and climate extremes).

Case Study: Nyhavna, Trondheim, Norway

- Former industrial harbor, currently no heating/cooling infrastructure; three-phase development (2025 – 2040).
- Key flexibility assets: Borehole thermal energy storage (seasonal storage from waste incineration) + large seawater heat pump.

Flexibility KPIs

Indicator	Purpose	Range
Electricity Consumption Response (ECR) ^[9]	relative change in electricity consumption under variable vs. constant prices; indicates ability for price-responsive dispatch flexibility	- (%) ^a
Peak Load Adjustment (PLA) ^[10]	relative change in peak electricity demand under variable pricing; assesses peak shaving potential to reduce grid strain	- (%) ^a
Operational Flexibility Range (OFR) ^[8]	quantifies operational adaptability via convex hull area of normalized electricity vs. thermal supply; larger range indicates greater flexibility	0 - 1 (-) ^b
Thermal Generation Utilization (TGUR) ^[11]	evaluates utilization of thermal generation capacity (0 % = unused, 100 % = full load); low values = limited downward flexibility; high values = limited upward flexibility	0 - 100 (%) ^b
Storage to Peak Ratio (SPR) ^[12]	relates storage energy capacity to peak demand (hours of possible peak supply if fully charged); indicates capability for temporal load shifting	0 - 3000 (h) ^c
Thermal Storage Utilization Factor (TSUF)	assesses storage cycling intensity (0 % = unused, 100 % = max throughput); high values = active load balancing; low values = underutilized	0 - 100 (%) ^b

^a Novel indicator. ^b Range based on technical system constraints. ^c Range based on literature benchmarks

System Performance KPIs

Indicator	Purpose	Range
Levelized Cost of Thermal Energy (LCOT) ^[13]	calculates break-even price per MWh for long-term economic viability; enables cost benchmarking across systems	10 – 288 (€/MWh _{th}) ^c
Electrification Share (ES)	measures share of thermal energy from electricity-dependent technologies; high share = higher flexibility potential for sector coupling	0 – 100 (%) ^b
Thermal Carbon Intensity (TCI) ^[14]	quantifies CO ₂ emissions per thermal energy; assesses environmental performance and decarbonization progress	30 – 120 (kg CO ₂ /MWh _{th}) ^c

^a Novel indicator. ^b Range based on technical system constraints. ^c Range based on literature benchmarks

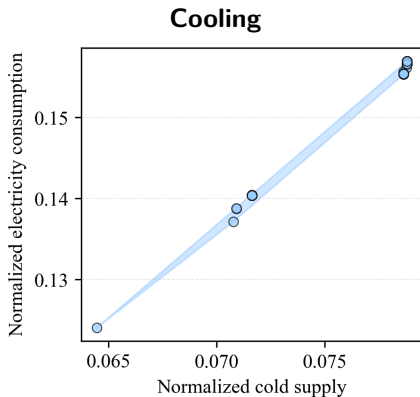
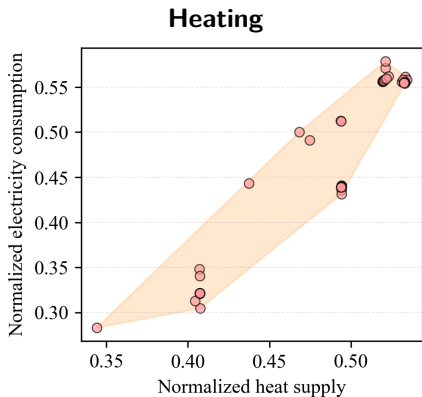
Base Scenario 2030 – Flexibility KPIs

Key Finding: Heating subsystem dominates operational flexibility; cooling contributes negligibly in Norwegian climate.

System-wide indicators		Unit	Value		Range					
Electricity Consumption Response (ECR)	%	-14.35				±20	↓	±5		
						favorable	acceptable	unfavorable		
Peak Load Adjustment (PLA)	%	0				-10	↓	+5		
						favorable	acceptable	unfavorable		
Subsystem-specific indicators		Unit	Heat	Cool	Range					
Operational Flexibility Range (OFR)	-	1.42×10^{-2}	1.51×10^{-5}				0.05	↓	0.01	↓
					favorable	acceptable	unfavorable			
Thermal Generation Utilization Rate (TGUR)	%	49.52	8.60				20	40	60	80
					unfav.	acc.	fav.	acc.	unfav.	
Storage to Peak Ratio (SPR)	h	2.87	17.06				200	↓	0	↓
					favorable	acceptable	unfavorable			
Thermal Storage Utilization Factor (TSUF)	%	39.50	9.28				60	↓	20	↓
					favorable	acceptable	unfavorable			

Operational Flexibility Range (OFR)

Key Finding: Convex hull visualization reveals heating's broad operational envelope versus cooling's constrained operation.



Base Scenario 2030 – System Performance KPIs

Key Finding: Heating is economically competitive, while cooling exhibits elevated costs. High electrification enables flexibility but creates exposure to grid conditions.

Indicator	Unit	Heat	Cool	Range
Levelized Cost of Thermal Energy (LCOT)	€/MWh _{th}	34.49	84.59	<div style="display: flex; justify-content: space-between; align-items: center;"> <div style="background-color: #d9ead3; padding: 5px;">favorable</div> <div style="background-color: #fff2cc; padding: 5px;">acceptable</div> <div style="background-color: #f4cccc; padding: 5px;">unfavorable</div> </div> <div style="display: flex; justify-content: space-between; margin-top: 5px;"> ↓40 ↓8 </div>
Electrification Share (ES)	%	88.49	100	<div style="display: flex; justify-content: space-between; align-items: center;"> <div style="background-color: #d9ead3; padding: 5px;">favorable</div> <div style="background-color: #fff2cc; padding: 5px;">acceptable</div> <div style="background-color: #f4cccc; padding: 5px;">unfavorable</div> </div> <div style="display: flex; justify-content: space-between; margin-top: 5px;"> ↓ ↓ 60 20 </div>
Thermal Carbon Intensity (TCI)	kg CO ₂ /MWh _{th}	74.45	6.35	<div style="display: flex; justify-content: space-between; align-items: center;"> <div style="background-color: #d9ead3; padding: 5px;">favorable</div> <div style="background-color: #fff2cc; padding: 5px;">acceptable</div> <div style="background-color: #f4cccc; padding: 5px;">unfavorable</div> </div> <div style="display: flex; justify-content: space-between; margin-top: 5px;"> ↓ 40 ↓ 100 </div>

Temporal Evolution 2025 – 2040: Flexibility

Key Finding: Heating flexibility undergoes substantial transformation, while cooling remains stable. No peak load modulation capability throughout planning horizon.

Indicator	Sec.	Unit	2025	2030	2035	2040	Range
Electricity Consumption Response (ECR)	-	%	5.94	-14.35	1.33	2.91	<p>±20 ±5</p> <p>favorable acceptable unfavorable</p>
Peak Load Adjustment (PLA)	-	%	0.00	0.00	0.15	0.27	<p>-10 +5</p> <p>favorable acceptable unfavorable</p>
Thermal Gen. Utilization Rate (TGUR)	Heat	%	41.18	49.52	54.20	54.35	<p>20 40 60 80</p> <p>unfav. acc. fav. acc. unfav.</p>
	Cool		9.54	8.60	9.50	9.47	
Storage to Peak Ratio (SPR)	Heat	h	3.39	2.87	5.54	9.58	<p>200 10</p> <p>favorable acceptable unfavorable</p>
	Cool		15.47	17.06	15.51	15.51	
Thermal Storage Utilization Factor (TSUF)	Heat	%	21.14	39.50	36.09	24.30	<p>60 20</p> <p>favorable acceptable unfavorable</p>
	Cool		11.76	9.28	11.58	11.47	

Temporal Evolution 2025 – 2040: System Performance

Key Finding: Rapid electrification (2025 – 2030) drives dramatic decarbonization of heating. Cooling maintains stable low-carbon performance throughout.

Indicator	Sec.	Unit	2025	2030	2035	2040	Range
Electrification Share (ES)	Heat	%	65.11	88.49	95.78	95.31	
	Cool		100.00	100.00	100.00	100.00	
Thermal Carbon Intensity (TCI)	Heat	kg CO ₂ / MWh _{th}	190.82	74.45	39.67	42.53	
	Cool		6.41	6.35	6.44	6.46	

Key Takeaways

- Heating dominates DHC flexibility, while cooling is negligible. No peak load modulation.
- Novel KPI framework shifts paradigm from thermal output to systematic flexibility assessment.
- Transferable methodology enables systematic comparison and benchmarking of DHC configurations.
- Supports flexibility-oriented DHC planning, policy development, and grid integration.

Relevant Literature I

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- [7] Konstantin Löffler et al. "Designing a Model for the Global Energy System—GENeSYS-MOD: An Application of the Open-Source Energy Modeling System (OSeMOSYS)". In: *Energies* (Sept. 2017). ISSN: 1996-1073. (Visited on 09/14/2025).

Relevant Literature II

- [8] Sebastian Zwickl-Bernhard et al. "Optimizing district energy systems under uncertainty: Insights from a case study from Washington D.C., USA". In: *Energy Conversion and Management* (Oct. 2025). ISSN: 01968904. (Visited on 09/14/2025).
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- [10] Rongxin Yin et al. "Quantifying flexibility of commercial and residential loads for demand response using setpoint changes". In: *Applied Energy* (Sept. 2016). ISSN: 03062619. (Visited on 12/01/2025).
- [11] Christian Finck, Rongling Li, and Wim Zeiler. "Optimal control of demand flexibility under real-time pricing for heating systems in buildings: A real-life demonstration". In: *Applied Energy* (Apr. 2020). ISSN: 03062619. (Visited on 12/01/2025).
- [12] Rafat Hirmiz et al. "Performance of heat pump integrated phase change material thermal storage for electric load shifting in building demand side management". In: *Energy and Buildings* (May 2019). ISSN: 03787788. (Visited on 12/01/2025).
- [13] Eftim Popovski et al. "Technical and economic feasibility of sustainable heating and cooling supply options in southern European municipalities-A case study for Matosinhos, Portugal". In: *Energy* (June 2018). ISSN: 03605442. (Visited on 12/01/2025).
- [14] David Blum et al. "Building optimization testing framework (BOPTTEST) for simulation-based benchmarking of control strategies in buildings". In: *Journal of Building Performance Simulation* (Sept. 2021). ISSN: 1940-1493. (Visited on 12/01/2025).

Cross-Scenario Comparison: Flexibility

Key Finding: Flexibility indicators reveal remarkable stability across all scenarios. Minimal variation despite substantial differences in market prices, climate conditions, and policy frameworks.

Indicator	Sec.	Unit	(1) Reference	(2) High Price	(6) Green Friendly	(9) Cold Winters	(10) Hot Summers	(14) High Carbon	Range
Electricity Consumption Response (ECR)	-	%	-14.35	-15.38	-14.69	-14.76	-16.23	-14.80	±20 ±5 favorable acceptable unfavorable
Peak Load Adjustment (PLA)	-	%	0.00	0.00	0.00	0.00	0.00	0.00	-10 +5 favorable acceptable unfavorable
Thermal Gen. Utilization Rate (TGUR)	Heat Cool	%	49.52 8.60	49.48 8.60	49.52 8.60	49.50 8.60	49.49 9.52	49.49 8.60	20 40 60 80 unfav. acc. fav. acc. unfav.
Storage to Peak Ratio (SPR)	Heat Cool	h	2.87 17.06	2.87 17.06	2.87 17.06	2.87 17.06	2.87 15.51	2.87 17.06	200 10 favorable acceptable unfavorable
Thermal Storage Utilization Factor (TSUF)	Heat Cool	%	39.50 9.28	44.33 9.28	39.50 9.28	39.50 9.28	43.30 11.67	39.50 9.28	60 20 favorable acceptable unfavorable

Cross-Scenario Comparison: System Performance

Key Finding: Economic performance varies substantially (LCOT: 15–24% variation between scenarios), while electrification and emissions remain stable, being structurally determined rather than policy responsive.

Indicator	Sec.	Unit	(1) <i>Reference</i>	(2) <i>High Price</i>	(6) <i>Green Friendly</i>	(9) <i>Cold Winters</i>	(10) <i>Hot Summers</i>	(14) <i>High Carbon</i>	Range
Levelized Cost of Thermal Energy (LCOT)	Heat	€/MWh _{th}	34.49	35.03	32.31	33.93	34.61	37.29	
	Cool		84.59	84.74	68.31	84.59	82.70	84.59	
Electrification Share (ES)	Heat	%	88.49	88.47	88.48	88.45	88.46	88.43	
	Cool		100.00	100.00	100.00	100.00	100.00	100.00	
Thermal Carbon Intensity (TCI)	Heat	kg CO ₂ / MWh _{th}	74.45	74.40	74.44	74.62	74.34	74.73	
	Cool		6.35	6.35	6.35	6.35	6.43	6.35	

Installed capacities

