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SCUOLA DI INGEGNERIA INDUSTRIALE E DELL'INFORMAZIONE

Executive Summary of the Thesis

Waste heat recovery from data centers for urban heating via 4th/5th generation networks: a methodology for thermo-economic analysis.

Laurea Magistrale in Energy Engineering - Ingegneria Energetica

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List of abbreviations

Acronym	Description
DC	Data Center
DHC	District Heating and Cooling
4/5GDHC	4th/5th Generation Hybrid Networks
WHR	Waste Heat Recovery
LCOH	Levelized Cost Of Heat
TES	Thermal Energy Storage
COP	Coefficient Of Performance
DHW	Domestic Hot Water
KPI	Key Performance Indicators
BO	Bayesian Optimization
MST	Minimum Spanning Tree
CAPEX	Capital Expenditure
OPEX	Operating Expenditure
BAU	Business As Usual
WCS	Worst Case Scenario
BCS	Best Case Scenario
ESCo	Energy Service Company
LCA	Life Cycle Assessment
GIS	Geographic Information System
EPBD	Energy Performance of Buildings Directive

1. Introduction

The current energy transition towards climate neutrality requires a profound restructuring of urban heat management, repositioning data center (DC) infrastructure as strategic thermal prosumers within a circular energy paradigm. Nearly all the electrical energy consumed by servers is converted into waste heat, which, rather than being dissipated into the atmosphere, can be integrated into advanced thermal networks to promote urban decarbonization [3]. This research focuses on integrating this waste heat into fourth- and fifth-generation hybrid networks (4/5GDHC) [2], a flexible architecture that overcomes the rigidity of traditional systems. Operating at intermediate temperature regimes, these hybrid circuits enable a dual-interface logic: users with compatible loads are served via direct heat exchange (4G), while the same infrastructure serves as an energy source for decentralized heat pumps (5G) [1] to power higher-temperature terminals such as radiators or domestic hot water tanks. The higher network temperature obtained from the waste heat of the DCs allows the heat pumps to work with better COP and avoid temporary service disruptions caused by defrost cycles. However, in the Italian market, these systems face significant economic barriers related to high investment costs and electricity prices, often making centralized networks less competitive than individual solutions unless rigorously optimized. In this regard, the study conducts a thermo-economic analysis from the perspective of an Energy Service Company (ESCo) to assess the technical and economic feasibility of implementing this technology.

2. Goals and Methodology

The research aims to define and validate a set of Key Performance Indicators (KPIs) to assess the technical and economic feasibility of waste heat recovery (WHR) from data centers. From a technical perspective, the study aims to establish scalable metrics such as the heat recovery rate ($WHR\%$) and specific sizing indicators that correlate recoverable thermal power with the heated surface area of buildings (m^2). From an economic perspective, the analysis aims to determine the system's competitiveness through the Levelized Cost Of Heat ($LCOH$), comparing it with stand-alone air-to-water heat pumps, including real-world issues such as defrost cycles. The study focuses on two main data center cooling technologies: air cooling (waste heat temperature 15-20°C) and liquid immersion cooling (waste heat temperature 40-45°C). The method, implemented in the MatLab R2022b environment, is based on an hourly dynamic simulation (8760 hours) of energy flows. The core of the system is the Energy Center, where the energy balance of the thermal storage tank (TES) is governed by the equation:

$$Q_{TES,t} = Q_{DC,t} + W_{EC,t} - Q_{dist,t} - Q_{loss,t}$$

The storage temperature (T_{acc}) is updated instant by instant following the law of conservation of energy:

$$T_{acc}(i+1) = T_{acc}(i) + \frac{B(i) \cdot 3600}{V_{acc} \cdot \rho \cdot c_p}$$

The distribution follows a hybrid logic: if T_{acc} is sufficiently high, the system operates in 4G mode (passive exchange); otherwise, 5G mode is activated via decentralized booster heat pumps. The electrical consumption of these units is calculated dynamically:

$$W_{load}(i,j) = \frac{Q_{load}(i,j)}{COP_{WWB}(T_{acc}(i) - 2, T_{supply,j})}$$

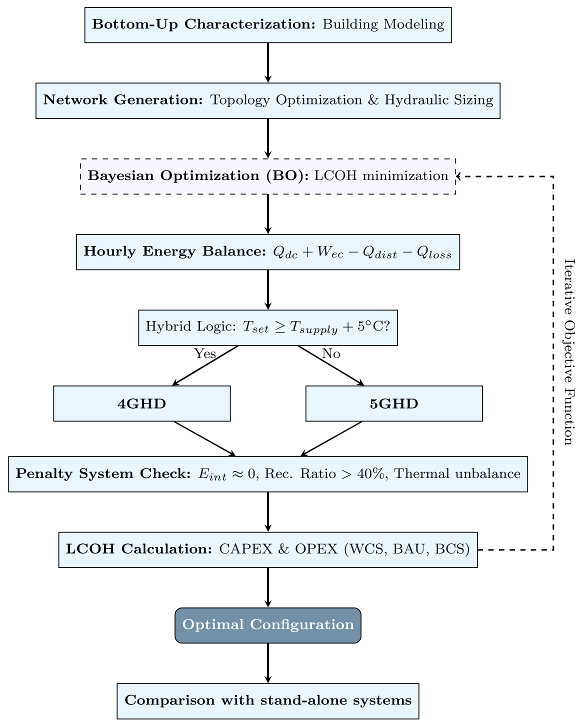

Figure 1: Integrated methodological flowchart.

To optimize the system, Bayesian Optimization (BO) is employed, which minimizes the LCOH by calibrating variables such as the set-point temperature (T_{set}), the storage volume (V_{acc}), and the data center power (P_{DC}).
The Levelized Cost Of Heat (LCOH) calculation is defined as the ratio between the present value of all costs incurred and the thermal energy actually recovered over the entire life cycle of the plant (n years):

$$LCOH = \frac{\sum_{t=1}^{n} \frac{CAPEX_t + OPEX_t}{(1+r)^t}}{\sum_{t=1}^{n} \frac{E_t}{(1+r)^t}}$$

In this formulation, CAPEX includes initial investments for the grid, substations and storage systems, while OPEX accounts for operating costs mainly related to the electricity consumption of heat pumps and maintenance; everything is discounted using a discount rate r to allow a direct comparison with the cost of heat generated by conventional systems in different market scenarios.
The method's originality lies in overcoming the static nature of traditional models. While the classical literature relies on generic building archetypes, this workflow integrates Google Maps and Open Meteo APIs for a granular, bottom-up characterization of the urban fabric

and real-world thermal loads. The use of the Minimum Spanning Tree (MST) algorithm for automatic network topology generation represents a significant breakthrough in model simplification, ensuring shorter implementation times at the expense of a slightly underestimated infrastructure CAPEX estimate. Furthermore, the adoption of BO, compared to common genetic algorithms, ensures superior computational efficiency in managing the "black-box" nature of the thermo-hydraulic model, balancing exploration and exploitation to identify optimal configurations in volatile economic scenarios (WCS, BAU, BCS). A key feature of this optimization process is the implementation of rigorous technical and physical constraints within the LCOH minimization objective function. By utilizing a penalty-based approach, the algorithm automatically discards configurations that fail to meet critical sustainability requirements, such as ensuring a minimum heat recovery ratio (typically >40%), avoiding long-term thermal drift in the storage system, and mandating that the energy center operates without reliance on external fossil fuel integration ($E_{int} \approx 0$). This methodological approach introduces significant improvements over the work of Buffa et al. (2019) [1], refining spatial accuracy through building-by-building analysis instead of aggregate profiles, and compared to Wirtz et al. (2020) [4], overcoming the rigidity of fixed network configurations through automated topology generation and the inclusion of dynamic operational constraints.

3. Case studies

The case studies analyzed focus on seven heterogeneous groups of buildings located in the municipality of Milan, selected to represent the diversity of the urban fabric and test the resilience of hybrid 4/5GDHC networks. The case studies include several residential buildings characterized by different construction periods, ranging from the post-war period to more recent constructions. A key assumption of the analysis is the hypothesis of a fully renovated building stock, in line with the strategic targets of the EPBD IV directive and the italian Ministerial Decree of June 26, 2015, for renovations after 2021 in climate zone E. This condition imposes minimum requirements for the thermal performance of buildings, with the goal of decarbonizing the building sector. The resulting building envelope efficiency not only ensures economic sustainability by reducing operating costs, but also promotes the optimal integration of low-temperature sources.

Case study	Spec. Heat. Demand [kWh/m^{2}y]	Spec. Total Demand [kWh/m^{2}y]	Spec. Peak Power [W/m^2]
MI 003	64.13	84.95	41.51
MI 004	55.53	76.35	36.17
MI 005	56.58	77.40	36.85
MI 006	54.27	75.09	35.35
MI 007	55.17	75.99	35.93
MI 017	59.67	80.49	39.08
MI 019	54.62	75.44	35.58

Table 1: Summary of technical performance indicators for the analyzed case studies.

The dynamic simulation, validated against the CENED databases, uses climate data for Milan to determine the heating and DHW needs of the different case studies.
The case study analysis highlights a marked homogeneity in the technical results, attributable to the methodological choice of modeling a completely redeveloped building stock. Nevertheless, it is possible to appreciate a slight differentiation in the specific heat demand mainly due to the different geometries of the buildings and therefore to the different shape factors (S/V).
A further case study was also analyzed for the conversion of an existing third-generation (3G) network to a hybrid 4/5GDHC architecture to exploit the possibility of reusing the existing infrastructure without having to build a new network. This choice minimizes capital expenditure (CAPEX), allowing for a significantly lower LCOH and making the system competitive with traditional heating technologies, but it introduces additional engineering challenges.
From a network hydraulics perspective, the reduction in heating load after renovation compensates for the reduction in the temperature difference ΔT_{new}. According to the equation $\dot{m}_{new} = Q_{post}/(c_p \cdot \Delta T_{new})$, if the drop in de-

mand is proportionally greater than the reduction in ΔT, the mass flow rate $\dot{m}$ does not exceed the limits of the original system. This synergy prevents hydraulic saturation of the existing pipes and limits the pumping power P_{pump}, which depends quadratically on the flow rate through pressure drops. Furthermore, since the heat demand is reduced, it is possible to power the existing terminals at lower temperatures as low temperature radiators (50°C) or install fancoils (45°C), compatible with 4G regimes or with the integration of booster heat pumps (5G).

4. Results

Despite the heterogeneity in network configurations, the waste heat management of data centers within 4/5GDHC hybrid networks follows recurring thermal dynamics, with a storage tank temperature (TES) that consistently stabilizes in the range between 55°C and 60°C, ensuring compatibility with low-temperature emission systems.

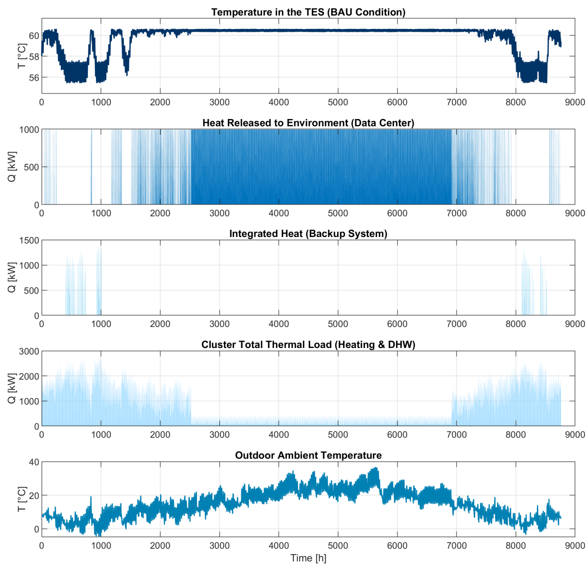

Figure 2: Analysis of the annual hourly trend of the main characteristic variables of the network for a case study with a liquid-cooled DC coupled network.

This thermal stability, however, faces a significant seasonal lag between the constant heat production of servers and the fluctuating demand of urban users: during the summer months, the drop in thermal demand causes the system to rapidly saturate the storage tank, causing the forced dissipation of recovered heat to prevent overheating of the network.

Meanwhile, in the winter, overall demand, driven by heating and domestic hot water production, exceeds the data center's production capacity, requiring external integration to cover load peaks when the outside temperature drops below critical thresholds.

Economically, the Levelized Cost Of Heat (LCOH) calculation demonstrates the clear superiority of integrated district heating compared to decentralized solutions based on stand-alone air-to-water heat pumps. While the autonomous system has an average thermal energy cost of approximately 96.98 €/MWh in the BAU scenario, penalized by direct dependence on the electricity market and inefficiencies resulting from defrosting cycles, centralized networks significantly reduce this threshold. Specifically, the configuration powered by air-cooled data centers achieves an LCOH of 76.19 €/MWh, benefiting from the financial compensation mechanism for the cooling service provided to the ICT infrastructure, a contribution that drastically reduces the net cost for the grid operator.

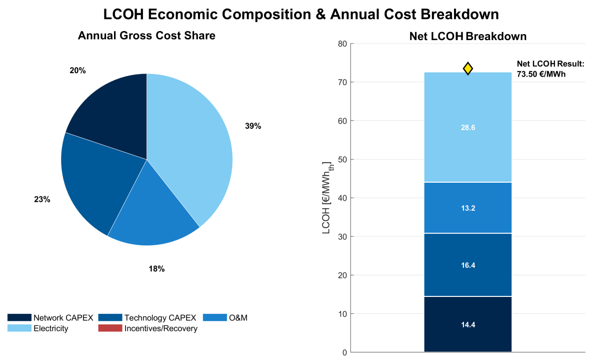

Figure 3: LCOH cost composition for a liquid-cooled DC-coupled grid case study.

However, the switch to liquid cooling represents the optimum in terms of cost and performance, reaching a value of 74.11 €/MWh. In this scenario, the savings are not solely due to monetary incentives, but rather stem from a higher intrinsic thermodynamic efficiency, where higher source delivery temperatures improve the COP of booster heat pumps, reducing the impact of electricity costs from 54% to just 43% of the gross cost and making the system much more resilient to energy price fluctuations. The proposed conversion of existing networks further reinforces this trend, as reusing exist-

ing pipes eliminates much of the infrastructure CAPEX, bringing the LCOH to approximately 70 €/MWh and consolidating the competitiveness of next-generation district heating.
The effectiveness of the recovery strategy is also confirmed by the environmental impact analysis, where all the configurations analyzed allow for a reduction in $CO2$ emissions of more than 45% compared to traditional condensing boilers, with the liquid system standing out as the most sustainable solution, with average specific emissions of 55.82 kg_{CO_2}/MWh.
To support future design, the research has crystallized precise dimensional parameters, defined as Key Performance Indicators, which serve as benchmarks: the installed power density relative to the heated surface area increases from approximately 9.93 W/m^2 for air-cooled systems to 15.43 W/m^2 for liquid-cooled systems, reflecting the latter's greater thermal extraction capacity, while the specific storage volume remains consistently around 52 L/m^2. This data suggests that, once a high standard of building envelope efficiency is achieved, the optimal system inertia is dictated primarily by the building's load profiles rather than the source's technological specifications, transforming the energy-critical nature of data centers into a stable and decarbonized urban resource.

5. Conclusions

In conclusion, the research confirms that integrating data centers into hybrid grids represents a solid investment opportunity that ensures a structural reduction in dependence on fossil fuels. The results highlight how the ability to precisely map the territory using digital tools overcomes the limitations of traditional thermal analyses, offering ESCos a reliable decision-making model for managing the heterogeneity of urban users. This paradigm transforms waste heat into a constant and predictable resource, increasing the resilience of the local energy system and stabilizing long-term operating costs, protecting the operator from fluctuations in primary energy and gas prices.
Looking to future developments, the work lays the foundation for the integration of machine learning—specifically Bayesian optimization—for the predictive management of thermal loads. Furthermore, a transition towards a comprehensive Life Cycle Assessment (LCA) will be essential to evaluate the total environmental impact beyond operational savings, while the adoption of GIS-based tools following urban street morphology will refine the current Minimum Spanning Tree (MST) topology for more realistic infrastructure modeling. Finally, the model's scalability across different latitudes and climates will consolidate this urban industrial symbiosis as a universal solution for the smart cities of the future.

References

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