Optimal operational strategy for waste heat recovery from an IT servers' room in a university campus

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Abstract. Waste heat recovery in data centres can be an effective strategy to reduce both the overall energy consumption of the server room and the space heating in nearby buildings. Considering the complexity of the interactions between cooling, heat recovery, and building heating systems, this study aims to evaluate the operational integration of data-centre waste heat recovery under realistic demand constraints. This is assessed using a Mixed-Integer Linear Programming (MILP) optimization framework focusing on a case study that includes a university building from the Politecnico di Milano campus and an IT server room, considering a water-to-water heat pump for waste heat recovery. Results show that waste heat recovery reduces the Power Usage Effectiveness (PUE) from 1.59 to 1.50 – 1.46 and produces an Energy Reuse Factor (ERF) from 14.5% to 21%. Annual financial savings range from 34k to 49 k€, while equivalent CO_2 emissions are reduced by 18%-26%. Evaluation of different extended heating schedules with early start results in the best overall performance, highlighting the importance of heating load profile optimization for better waste heat utilization.

1 Introduction

The rapid expansion of digital technologies, such as 5G, artificial intelligence and cloud computing, has made data centres a major driver of electricity demand, with global consumption rising from about 460 TWh in 2022 to a projected over 1000 TWh by 2026 [1]. Italy is also increasingly allocating economic resources to data centre infrastructure, with approximately €5 billion invested in the 2023–2024 period and a further €10.1 billion projected for 2025–2026, reflecting the growing strategic importance of the sector at the national level [2]. Data centres together with cryptocurrencies and artificial intelligence, already reached 2% of total global electricity demand worldwide in 2022 which was mainly associated with computing and cooling. [3] estimate that cooling accounts for 30–50% of total data centre energy use.

From an energy management perspective, data centres have the capability to transition from purely high-energy consumers to active energy contributors through waste heat recovery and reuse. This potential arises from the substantial amount of heat generated by IT

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equipment and cooling systems, which represents a valuable thermal resource. When efficiently captured and repurposed, this waste heat can help reduce energy losses, enhance sustainability, and support integration into broader district heating (DH) networks [4]. As a result, waste heat recovery is widely recognized as an effective strategy to improve overall energy efficiency, achieve energy and cost savings, and mitigate environmental impacts [5, 6].

Several works have focused on cooling applications, such as silica gel–water adsorption refrigeration driven by data centre waste heat [7, 8, 9] and waste-heat-driven absorption chillers [10]. Moreover, the reuse of waste heat for district heating and space heating has been widely explored, particularly through the integration of heat pumps to upgrade the temperature level of the recovered heat. [4] experimentally demonstrated that a heat recovery system based on a three-fluid heat exchanger and a heat pump can achieve a comprehensive energy efficiency ratio (CEER) up to 4.47 at a supply temperature of 50 °C, with an annual average value of 4.75 under cold climate conditions, highlighting its strong potential for district heating applications. Similarly, [11] showed that an integrated air-conditioning system with a thermosyphon can effectively recover data centre waste heat for space heating, significantly improving overall system energy efficiency and reducing conventional heating demand. Waste-heat recovery water-source heat pump integration between data centres and residential heating has been reported to reduce PUE from 1.26 to 1.23, lower data centre and residential energy consumption by 12.3% and 31.2%, respectively, and decrease total energy use and lifecycle CO_2 emissions by 18.8% and 28.7% under cold climate conditions [12].

More recently, hybrid and integrated system-level solutions combining high-efficiency cooling and waste heat recovery have been proposed to improve overall energy utilization and balance environmental and economic performance in data centres [13, 14]. Latest systematic reviews synthesize waste heat recovery pathways in data centres, covering heat collection from different cooling technologies, heat upgrading solutions such as heat pumps and thermal energy storage, and end-use applications including district heating, cooling, and power generation. These studies highlight significant potential benefits in terms of PUE reduction, economic performance, and carbon emissions mitigation [15, 16].

Simulation-based campus-scale studies show that integrating data centre cooling with aquifer thermal energy storage (ATES) can reduce average PUE from about 1.78 for conventional cooling to approximately 1.56–1.45, depending on the operational configuration, while also enabling significant energy and CO_2 emission reductions [17]. Further campus-based studies have examined the integration of data centre waste heat into district heating networks using thermal energy storage to address supply–demand mismatch, showing that water tank storage can reduce peak loads by about 31%, while borehole storage can increase waste heat utilization up to 96% and reduce annual CO_2 emissions by around 8% [18]. Recent studies have further explored the optimization of integrated data centre cooling and waste heat recovery systems using mixed-integer linear program-ming (MILP), demonstrating measurable improvements in system performance and reductions in PUE [19].

Within the research landscape outlined in the literature on data centre waste heat recovery, this paper contributes to ongoing efforts to quantify and optimize waste heat integration at building and campus scale and is developed within the framework of the EU-funded HYCOOL-IT project. This project aims to establish standardized processes supported by innovative digital and technical solutions to enable the efficient and reliable implementation of IT server rooms in advanced tertiary buildings, with particular emphasis on replicability and performance-driven design.

As data-centre electricity demand continues to grow, MILP-based system-level optimization offers a useful framework to translate the established potential of waste-heat recovery into operational strategies that explicitly account for constraints and real demand profiles. In this context, this work aims to assess the performance of waste-heat recovery integration using Mixed-Integer Linear Program-ming (MILP) models and numerical simulations. The study is conducted at the Politecnico di Milano and focuses on the operational coupling between an IT server room and an adjacent university building. The coupling between the data-centre cooling system, a water-to-water heat pump, and the building space-heating system is investigated. To this end, a system model and a MILP optimization problem are developed to determine the optimal operating strategy, i.e., the one that minimizes the energy cost. Considering three different heating schedules with progressively earlier start times of the heating system, simulations were carried out; for each schedule, results obtained with heat recovery are compared with a reference scenario without heat recovery. Performance is assessed using PUE and ERF indicators, while energy savings are quantified together with the corresponding financial benefits and equivalent CO_2 emission reductions.

2 Description of the case study: POLIMI BL26 building and Z3 server room

Building “BL26” of Politecnico di Milano is located at La Masa Campus in Milan, Via Lambruschini 4 (Fig. 1) and it was completed in 2008. It is a university building complex that contains offices, classrooms, the Management Engineering Department (DIG) and the Politecnico di Milano Graduate School of Business (GSoM) with a total floor area of around 15’800 m^2 and a net climatized area around 10’300 m^2. It consists of four bodies, spread over 4–5 levels, from the basement to the fourth floor. In terms of space heating and cooling needs, the HVAC system servicing this building consists of two boilers and two chillers. The boilers provide heating in winter, while the chillers handle air conditioning during summer. Heating season goes from October 15th until April 15th, and the annual space heating demand per m^2 of floor area is approximately 84 kWh/m^2. The “Z3” server room is a small data centre located at the Politecnico di Milano with a climatized area of 150 m^2. The room’s internal architecture includes servers placed in four rows of racks which are grouped in two hot aisle containments. Server average monthly load is 95 – 100 kW, while average annual PUE from monitoring data is equal to 1.6. Server rack cooling is done by means of an in-row cooling strategy that uses twelve “In-Row Half Rack RC” terminals with two cooling distribution units. Two chillers are used for producing the chilled water for in-row cooling.

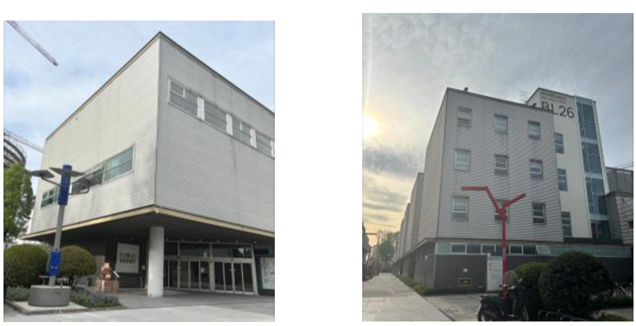

Fig. 1 Building BL26 exterior views.

3 MILP model background

A Mixed Integer Linear Programming (MILP) problem is formulated to find the optimal operational strategy, which is based on the minimization of the energy bill. In principle, 12 typical days, one for each month, are analyzed. If a month is split in two by the beginning or the end of the heating season, the corresponding typical day is also split in two and each portion is analyzed separately, as different conditions apply depending on the presence of heating demand. Therefore, the number of typical days analyzed can be 14 at maximum. In each typical day, the partial energy bill used for the optimization is the sum of the expenditures for electricity and natural gas of the combined system (server room cooling and building space heating) in each hour of the day "t" (1...24).

3.1 Cooling system with waste heat recovery strategy

The considered cooling scheme for the heat recovery integration is shown in Fig. 2, where the cooling system is composed of air-cooled chillers (two due to redundancy) and a water-to-water heat pump for waste-heat recovery. It can be used in either partial or full free cooling mode, taking advantage of the separate rows from the condenser's finned tube coils as shown in Fig. 2. If the outside temperature is low enough, partial free cooling can be done, where a fraction of water is sent to the condenser's separate loop for free cooling. An "intelligent free cooling" mode can also be considered, where the finned tube coils from the con-denser of the second chiller are used to increase the heat exchange area for free cooling. Even though this second chiller unit is turned off, the condenser's fan can be turned on, and its coils can be used for free cooling. By increasing the area for more heat exchange between the water and outside air, it is possible to further reduce the evaporator's cooling load and compressor's consumption. Waste-heat recovery is done by means of a heat pump and heat exchanger installed before the chiller units, as illustrated in Fig. 2. The configuration not only reduces compressor energy consumption but also enables the parallel operation of waste heat recovery and free cooling. Considering that waste-heat recovery and free cooling don't block each other in this configuration, energy for space heating applications can be provided while also obtaining savings with free cooling.

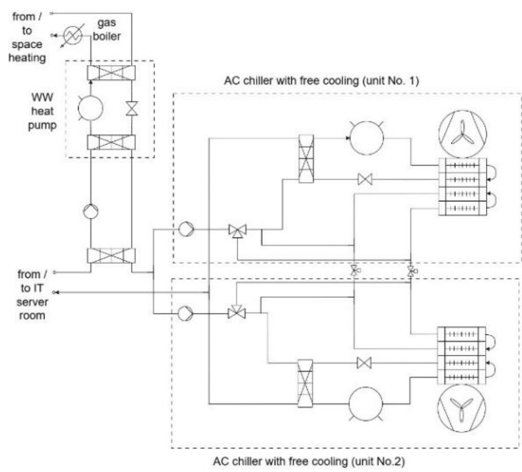

Fig. 2. Cooling scheme with waste-heat recovery and free cooling.

3.2 Cooling scheme modelling equations

The objective function related to the cooling scheme is shown in Equation (1):

$$Obj = \sum_{t=1...24} (W_{ch}t + W_{fc}t + W_{hp}t + W_{pump}t) \cdot p_{el} + \sum_{t=1...24} (Q_{ng}t \cdot p_{gas}) \quad (1)$$

Where each element is identified as follows:

- $W_{ch}t$: power consumption of the chiller when the mechanical cooling is active;

- $W_{fc}t$: power consumption of the chiller in free-cooling mode, equal to $Q_{fc}t / EER_{fc}t$;
- $W_{hp}t$: power consumption of the heat pump used for heat recovery;
- $W_{pump}t$: power consumption of the circulation pump in the cold heat recovery pipeline;
- $Q_{ng}t$: gas input in the “t” hour to the gas boiler providing space heating to the building.

The term $W_{pump}t$ is represented as fixed fraction of the heat recovered from the main cooling circuit as heat source for the heat pump ($Q_{hr}t$), whereas $Q_{fc}t$, $W_{ch}t$ and $W_{hp}t$ are optimization variables. The chiller’s cooling power is calculated according to Equation (2), where $EER_{ch}t$ refers to the chiller’s energy efficiency ratio, calculated assuming a fixed temperature difference between the water leaving the condenser and the outdoor air. For each hour, $W_{ch}t$ is limited according to Equation (3).

$$Q_{ch}^t = EER_{ch}^t \cdot W_{ch}^t \tag{2}$$

$$0 \leq W_{ch}^t \leq W_{ch,max} \tag{3}$$

In a similar way, the heat pump’s useful heat is calculated as in Equation (4), considering an assumed COP value, while $W_{hp}t$ is limited in each hour according to Equation (5).

$$Q_{hp}^t = COP_{hp}^t \cdot W_{hp}^t \tag{4}$$

$$0 \leq W_{hp}^t \leq W_{hp,max} \tag{5}$$

The energy balance at the server room provides the constraint represented in Equation (6).

$$W_{IT}^t - H_{T,room} \cdot (T_{room} - T_{oda}^t) = Q_{ch}^t + Q_{fc}^t + Q_{hr}^t \tag{6}$$

In Equation (6), each element is described as follows:
- W_{IT}^t: heat dissipated by the IT servers;
- $H_{T,room}$: overall heat loss coefficient of the server room;
- T_{room}: air temperature inside the server room (assumed constant);
- T_{oda}^t: outdoor air temperature;
- Q_{fc}^t: cooling provided by the chiller coils in free-cooling mode;
- Q_{hr}^t: cooling provided by heat recovery, difference between Q_{hp}^t and W_{hp}^t.

Since the chiller coil capacity drops when the temperature difference between water and outdoor air decreases, Q_{fc}^t is limited according to the conditions depicted in Equation (7). In said equation, $Q_{fc,nom}$ is the heat rejection capacity of the chiller coils at nominal temperature difference water - outdoor air, $T_{chw,i}$ is the temperature of the chilled water returning to the chiller, and $\Delta T_{fc,nom}$ is the nominal temperature difference water - outdoor air for the free cooling coil.

$$0 \leq Q_{fc}^t \leq max\ (0;\ Q_{fc,nom} \cdot (T_{chw,i} - T_{oda})/(\Delta T_{fc,nom})) \tag{7}$$

Finally, the modelling scheme also includes the energy balance at the building heating demand, where the space heating demand (Q_{sh}^t) is calculated according to Equation (8). In this equation, Q_{gb}^t is the useful heat generated by the gas boiler, and Q_{hp}^t is the heat generated by the heat pump.

$$Q_{sh}^t = Q_{gb}^t + Q_{hp}^t \tag{8}$$

Once Q_{gb}^t is calculated from the previous equation, the natural gas consumption is calculated as in Equation (9), considering the gas boiler's efficiency (η_{gb}).

$$Q_{ng}^t = Q_{gb}^t/\eta_{gb} \tag{9}$$

3.3 KPIs to evaluate energy recovery efficiency

Data centre energy recovery efficiency can be evaluated through two main parameters, being the Power Usage Effectiveness (*PUE*) and the Energy Reuse Factor (*ERF*). The PUE is the most used standard metric used to measure how efficient a data centre is; its calculation is detailed in Equation (10), being defined as the ratio between the total data centre energy consumption ($E_{DC,TOTAL}$) to the server IT equipment energy consumption ($E_{DC,IT}$). The *ERF* is defined as the ratio of the re-used energy to the total data centre energy consumption, as depicted in Equation (11). *PUE* values higher/equal than 2 indicate poor energy efficiency, values between 1.5 and 2 are considered fair, and efficient data centres typically have *PUE* values below 1.5. *ERF* ranges from 0 to 1, where an *ERF* of 0 means that no waste heat is recovered. Both *PUE* and *ERF* should be assessed over long periods (e.g., annually), as seasonal variations influence cooling demand and the amount of energy reused outside the data centre. Reducing cooling energy demand can lead to financial savings and lower equivalent CO_2 emissions. Recovering energy from the server room also reduces natural gas consumption for space heating, resulting in additional cost and emission savings. These financial and environmental benefits, together with *PUE* and *ERF*, are the main KPIs discussed in Section 4.

$$PUE = E_{DC,TOTAL} / E_{DC,IT} \tag{10}$$

$$ERF = E_{DC,Re\text{-}used} / E_{DC,TOTAL} \tag{11}$$

4 Performance assessment of MILP modelling for waste heat integration

4.1 Simulation inputs

Considered space heating schedules are listed in Table 1 while the hourly space heating load profiles considered for the typical day of each month of the heating season are presented in Fig. 3.

Table 1. Heating schedule for each case

Case	Heating hours
Baseline	6 a.m. – 7 p.m.
Schedule 2	4 a.m. – 7 p.m.
Schedule 3	10 p.m. – 7 p.m.

For the server room inputs, an overall loss coefficient ($H_{T,room}$) for thermal losses was calculated and equal to 472 W/K, IT equipment load is 100 kW, and a load factor of 15 % is assumed. Regarding building data, floor area is 10'300 m^2, and a space heating demand of 84 kWh/(m^2 y) is considered (heating period the same as the one in section 2.1). Natural gas and electricity equivalent CO_2 emission factors are considered 0.2 kg CO_{2eq}/kWh NCV [20] and 0.35 kg CO_{2eq}/kWh [21] respectively, while energy prices are taken as 0.11 €/kWh [22] and 0.33 €/kWh [23] for natural gas and electricity, respectively.

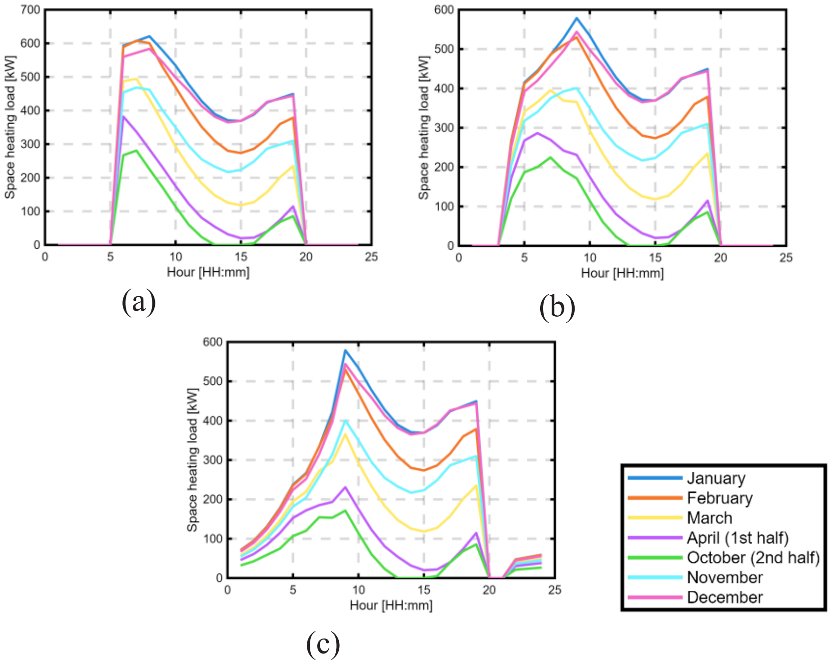

Fig. 3. Hourly space heating loads for typical days of heating season: (a) Baseline (b) Schedule 2 (c) Schedule 3.

4.2 Feasibility study

4.2.1 Baseline case results with and without heat recovery

Obtained *PUE* for the benchmark case was of 1.59, which is equal to the mean annual *PUE* obtained with monitoring data. Annual energy consumption for the cooling system without heat recovery integration resulted 381’568 kWh/y, while annual natural gas consumption for space heating was 1’017’882 kWh/y. After integrating the heat recovery scheme, the resulting annual *PUE* is 1.50, being a decrease of 6 % with respect to the baseline’s *PUE*. It’s clear that heat recovery influences the *PUE*, as the cooling system’s energy savings help decrease the *PUE* value. Due to heat recovery for space heating, the obtained *ERF* is of 14.50%. This means that more than 10 % of the total energy consumed by the server room can potentially be recovered for space heating. An improvement in terms of exploiting more waste-heat for other applications could be considered, including heat storage.

Fig. 4 presents the comparison between the cooling system’s energy consumption with and without heat recovery. When using heat recovery, the annual consumption of the server room’s cooling system was of 297’745 kWh/y, representing a reduction of 83’823 kWh/y with respect to the baseline scenario. Furthermore, as seen in Fig. 4, peak consumption during the summer season is equal for both cases, but the case with heat recovery has a lower consumption during the heating season thanks to the integration of free cooling, which allows to exploit the use of external air to further decrease the compressor’s load. Another aspect that helps to lower the consumption during the heating season is the use of heat recovery by the water-to-water heat pump, which allows to decrease the evaporator’s load in the chiller.

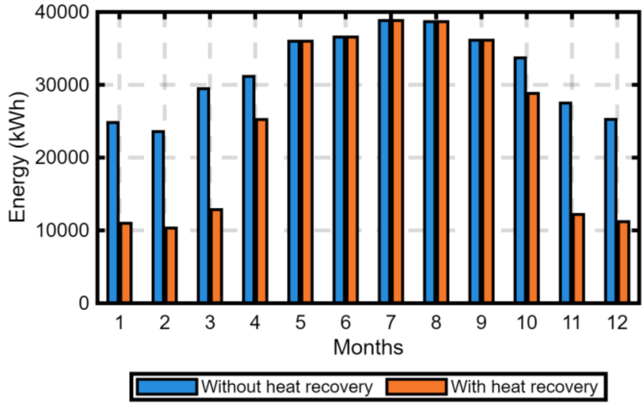

Fig. 4. Monthly electricity consumption for server room cooling with and without heat recovery.

Monthly natural gas consumption is depicted in Fig. 5, where the use of heat recovery means a reduction of 30.4 % with respect to the baseline case. During the entire heating season, natural gas consumption benefits in all months with the use of waste heat recovery, leading to annual savings of 309’810 kWh/y with respect to the baseline scenario.

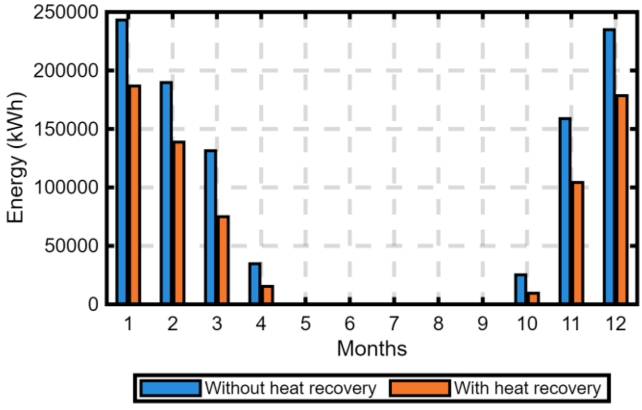

Fig. 5. Monthly natural gas consumption for building space heating with and without heat recovery.

Annual financial savings due to a decrease in energy consumption for cooling and space heating were calculated, with space heating financial savings equal to 8’533 EUR/y, while those for server cooling were of 27’662 EUR/y, for a total of 36’195 EUR/y. The previously analyzed energy consumption savings can also be translated into equivalent CO_2 emissions savings, both for the cooling system and space heating. Annual equivalent emission savings related to space heating where of 34’868 $kgCO_{2eq}$/y, while those related to server cooling resulted 29’338 $kgCO_{2eq}$/y. However, a final remark about the used waste-heat recovery scheme needs to be clarified. The studied cooling scheme contains a water-to-water heat pump for waste-heat recovery, which represents an extra electricity consumption that penalizes the financial and emission savings in space heating applications. To illustrate this point, the annual extra electricity consumption required for waste-heat recovery was equal to 77’412 kWh/y, which represents 25 % of the annual energy consumption of the cooling system with heat recovery. This is an important factor to consider as different heat recovery schemes could have a lower energy demand and thus a lower negative impact on savings.

4.2.2 Influence of heat recovery with different space heating profiles

The benchmark case was tested within the MILP model with the schedules previously listed in Table 1, and the *PUE* and *ERF*, along with energy consumption results, are presented in Table 2. It's important to point out that results from Table 2 compare the baseline scenario without heat recovery with schedules 2 and 3 using heat recovery. This way, an overall view of the influence of changing the space heating schedule with heat recovery can be analyzed. The increase in hours in which waste heat can be recovered leads to a further decrease in the *PUE*; as seen in the results of Table 2, the use of schedule 2 with heat recovery means a decrease of 6.8 % with respect to the baseline case. Moreover, schedule 3 represents a further decrease of 8.5 % with respect to the benchmark results. The continuous use of the heat pump for heat recovery applications helps to further decrease the load in the chiller's evaporator and benefits the *ERF*, increasing from 16.9 % to 21 % from schedule 2 to 3.

Results related to server room cooling energy consumption from Table 2 follow the trend already seen with the *PUE* analysis, as more hours in the heating schedule allows to further decrease the electricity for cooling. Considering the baseline result of 381'568 kWh/y for server room cooling, Schedule 2 produced savings of 95'442 kWh/y, while schedule 3 had savings of 118'834 kWh/y (an increase of 24.5 % with respect to Schedule 2). Regarding the boiler's natural gas consumption, schedule 2 with heat recovery presents a reduction of 29.3% compared to the baseline without heat recovery, while Schedule 3 improves the consumption considering a reduction of 41.4 %. An important point to clarify is that natural gas consumption is influenced not just by heat recovery but also by the space heating load profile (see Fig. 3); these results are therefore dependent on the specific load profiles and operational assumptions. The continuous use of a heat pump also produces an increase in required electricity for waste heat recovery. As highlighted in Table 2, the heat pump's energy consumption increases with more space heating hours. For schedule 2, the annual energy consumed by the heat pump was 89'234 kWh/y, which represents 31 % of the energy dedicated to server room cooling; moreover, for schedule 3, the auxiliary energy for the heat pump was 41 % of the annual cooling energy. This leads to the idea that a compromise is required to balance savings with auxiliary energy consumption for waste heat recovery.

Table 2. PUE, ERF, and energy consumption comparison between baseline case without heat recovery and new schedules with heat recovery

Case	PUE	ERF (%)	Energy for Cooling [kWh/y]	Natural Gas Consumption [kWh/y]	Energy for Heat Recovery [kWh/y]
Baseline (w/o HR)	1.59	-	381'568	1'017'882	-
Schedule 2 (with HR)	1.489	16.9	286'126	719'538	89'234
Schedule 3 (with HR)	1.462	21.0	262'734	596'687	109'180

Fig. 6 reports the total energy costs and savings comparing, like in Table 2, schedules 2 and 3 with heat recovery with the baseline case without heat recovery. Considering the energy savings already analyzed, it's possible to further highlight that the adoption of waste heat recovery systematically reduces the total (gas and electricity) annual energy bill with respect to the reference operation without heat recovery.

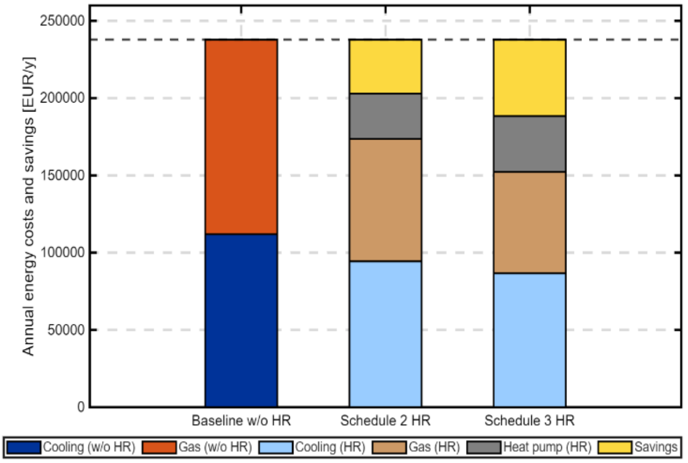

Fig. 6. Annual energy costs and financial savings for Schedule 2 and Schedule 3 obtained by adopting heat recovery compared with the baseline schedule without heat recovery.

Overall financial savings for schedules 2 and 3 are, respectively, 34’867 €/y and 49’517 €/y. A breakdown of the cost savings indicates that approximately 93 – 95% of the total annual reduction is driven by lower natural gas consumption, whereas the contribution from electricity remains comparatively limited because of the additional electricity demand required to operate the heat pump for heat recovery. Schedule 3 achieves the lowest overall energy cost thanks to its corresponding load profile (see Fig. 3) which brings forward the heating system start-up and redistributes the thermal demand over a wider time horizon. Consequently, peak hourly heating loads are reduced while the overall heating demand is still met, leading to a lower fuel requirement and therefore reduced natural gas use.

Fig. 7 shows that waste heat recovery also leads to a consistent reduction in annual equivalent CO_2 emissions for all schedules, with savings ranging from 61 tCO_2eq/y with schedule 2 to 88 tCO_2eq/y with schedule 3 (18 - 26%). In all cases, the dominant contribution refers to reduction in natural-gas-related emissions, while net electricity-related emissions change only marginally due to the heat pump’s electricity consumption. Schedule 3 also yields the lowest total annual equivalent CO_2 emissions among the evaluated heat recovery schedules, primarily due to the reduced natural gas demand for space heating.

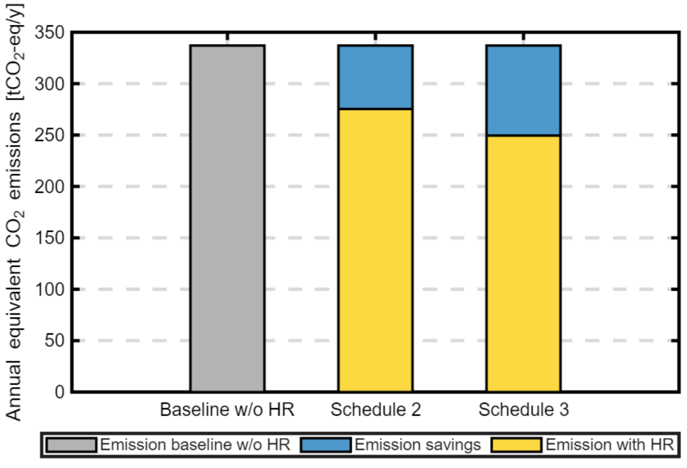

Fig. 7. Annual equivalent CO_2 emission savings for Schedule 2 and Schedule 3 obtained by adopting heat recovery compared with the baseline schedule without heat recovery.

Conclusions

This work evaluated, through MILP-based optimisation, the potential integration of data-centre waste heat recovery with a campus building heating system. Across all tested space heating schedules, results demonstrate that heat recovery integration can improve system performance, reducing *PUE* from 1.59 to 1.50 – 1.46 and increasing *ERF* from 14.5% to 21% within the assumptions of the adopted operational profiles. Relative to the baseline schedule without heat recovery, the proposed solutions achieved annual energy savings of approximately 34’867 €/y – 49’517 €/y and avoided about 61–88 tCO_2eq/y. Economic and environmental savings increased with greater availability of recoverable heat. These savings were largely driven by natural gas displacement (approximately 93–95 % of total cost savings), while net electricity savings remained limited because of electricity demand of the heat pump. Among the investigated schedules, schedule 3, characterized by extended heating operating hours, delivered the best performance, suggesting that schedule design and early heating start-up can improve waste heat utilisation. Results suggest that coupling waste heat recovery with operational optimisation has the potential to generate financial, energy and equivalent CO_2 emissions savings. Considering that heating schedules are based on generated assumptions, future work will focus on investigation of flexibility, to better ensure tangible savings during the operational phase.

Symbology

Symbol	Definition
$COP_{hp}{}^{t}$	Coefficient of performance of the heat pump, ND
$EER_{ch}{}^{t}$	Energy efficiency ratio of the chiller, ND
ERF	Energy Reuse Factor, ND
$H_{T,room}$	Overall heat loss coefficient of the server room, W/K
Obj	Objective function, €
$Q_{ch}{}^{t}$	Cooling power provided by the chiller in normal operation, kW
$Q_{fc}t$	Cooling power provided in free-cooling mode, kW
$Q_{hp}t$	Useful thermal power provided by the heat pump, kW
$Q_{gb}t$	Useful heat generated by the gas boiler, kW
$Q_{pipe}{}^{t}$	Heat loss through the pipeline, kW
$Q_{ng}{}^{t}$	Natural gas input in the "t" hour to the gas boiler providing space heating to the building, kW
$Q_{sh}t$	Building space heating demand, kW
$Q_{hr}{}^{t}$	Heat recovered, kW
p_{el}	Electricity price, €/kWh
p_{gas}	Gas price, €/kWh
PUE	Power Usage Effectiveness, ND
T_{hr}	Temperature of recovered heat, °C
T_{room}	Server room air temperature, °C
$T_{oda}{}^{t}$	Outdoor air temperature, °C
$T_{chw,i}$	Temperature of the chilled water returning to the chiller, °C
$\Delta T_{fc,nom}$	Nominal temperature difference water-outdoor air for the free cooling coil, °C
UA_{pipe}	Overall heat transfer coefficient of the pipeline, W/K
$W_{hp}{}^{t}$	Power consumption of the heat pump used for heat recovery, kW
$W_{hp,max}$	Maximum power consumption of the heat pump used for heat recovery, kW
$W_{ch}{}^{t}$	Power consumption of the chiller when the mechanical cooling is active, kW
$W_{fc}{}^{t}$	Power consumption of the chiller in free-cooling mode, kW
$W_{pump}{}^{t}$	Power consumption of the circulation pump in the cold heat recovery pipeline, kW
$W_{IT}{}^{t}$	Heat dissipated by IT equipment, kW

Greek symbols	
η_{gb}	Gas boiler efficiency, ND
$\delta_2{}^{t}$	Binary variable for heat recovery activation, ND

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