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Recovery of waste heat from data centres for decarbonisation of university campuses in a Mediterranean climate

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ABSTRACT

In this research work, the Stanford Energy System Innovations action plan is adapted to the decarbonization of the Universitat Politècnica de València, of the Mediterranean coast of Spain. Special focus is dedicated to waste heat recovery from a data centre located on campus with an almost constant cooling demand throughout the year, amounting to a yearly 1,661,020 kWh. To recover the waste heat generated by the data centre, a method for assessing thermal performance of the system is presented, which is implemented by selecting a 300 kW polyvalent heat pump (capable of easily switching from water-to-water to air-to-water working modes). It can simultaneously provide cooling and heating to a set of strategically identified buildings on the campus: the university data centre and three buildings located nearby that currently use the university's central natural gas boilers for heating. A thermal storage system is designed to balance the cooling and heating needs. The results lead to potential thermal energy savings of more than 254,106 kWh/year, and a consequent reduction in CO_2 emissions of at least 64,035 kg/year, supporting the decarbonization of the Vera campus. The outcomes of the study can help to design similar research projects applied to large data centres in Mediterranean cities.

1. Introduction

Cities are at the heart of EU policies to combat climate change [1]. A clear example is a first key mission to make 100 cities climate neutral by 2030 [2], as they currently produce 72% of global emissions and they will have 80% of the world's population by 2050. Valencia was selected by the EU in April 2022 as one of those 100 cities to become climate neutral by 2030. In this framework, actors from the public and private sector collaborate and interact. Among others, the academia is considered as one of the vital ecosystems in this process. For this reason, the Universitat Politècnica de València (UPV) signed an agreement in 2020 to become city ambassador of the decarbonization of Valencia. As such, it can implement best practices by acting as a sandbox environment, where those solutions for the decarbonization of UPV campus, can later be transferred to the city, and vice-versa. The target for UPV Vera Campus is also to become 100% carbon neutral by 2030, i.e. the yearly net balance of greenhouse gas (GHG) emissions should be equal to zero (currently under scopes 1 and 2).

Several universities worldwide have undertaken similar commitments, and smart sustainable campuses with innovative solutions are on the rise. An analysis by [3] studies 424 initiatives developed by universities around the world and concludes that most of the measures carried out are comparable and focus on energy systems and buildings. Most cases seek to improve the energy efficiency of buildings by changing their insulation, lighting system (LEDs) or HVAC systems (Heating, Ventilation and Air Conditioning), as well as with demand response and control devices to reduce or reschedule the building energy demand. Besides, the cases also propose to increase the generation of renewable energy, usually by installing solar photovoltaic panels. A different and interesting type of measure is the installation of displays that show the energy consumption of each building, making people aware of it. For example, the work by [4], real-time electricity consumption data were presented to students in real-time via a dedicated web platform, while, at the same time, appointing an energy delegate in each hall to induce motivation among the students. Immediate energy feedback from display devices provided savings of 5% to 15%. Similarly, in the work by [5] Information and Communication Technologies (ICT) were made to act upon Energy Management Systems to achieve energy

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savings through negotiating building environmental conditions with the users. Energy consumption could be reduced up to 40% in some pilots.

With regard to centralised and optimisable technologies, Heat Pumps (HPs) are a high energy efficient technology with a great potential to substitute fossil fuel production systems [6]. They contribute to their electrification, and are recognized as a renewable energy resource by [7]. In addition, a very interesting feature is that they can be used for low grade waste heat recovery [8], and can be also coupled with renewable energy systems and District Heating (DH) networks acting as booster HPs such as described in [9] for the performance of ultra low temperature district heating systems with booster heat pumps; also [10] who assesses the economic feasibility of booster heat pumps in heat pump-based district heating systems, or [11] where a triple function substation and high-efficiency micro booster heat pump is presented for Ultra Low Temperature District Heating Energy. This concept is part of the 4th generation DH with the objective of delivering heat in a more efficient way, and connected with renewable energy resources [12]. An added value of these systems is that they can interact with waste-heat coming from different sources.

Part of the waste-heat available on university campus comes from sports facilities and their showers and swimming pools. Another source of great potential is the waste heat generated in the data centres. Data centres consume a large amount of electrical energy that could be recovered up to a 97% as heat, as described in [13]. From these installations, a high amount of waste-heat can be fed in the waste-heat network in a fairly continuous basis [14]. This latter option was also found to be available on the UPV campus, as there is a large data centre located on the campus. It presents almost constant cooling needs all over the year, varying between 270 and 300 kW approximately, to overcome the internal gains generated by the operation of the servers and to maintain indoor ambient conditions around 19 to 21 °C.

There are many different cooling technologies for the data centres as described in [15], where the most promising methods and technologies for recovering data centre low temperature waste heat in an effective and economically reasonable way are identified and discussed. In the case of air-cooled data centres, which stand for the majority of existing data centres, the excess heat is discharged into the air, typically using a chiller or a cooling tower. The temperature range of this waste heat from air cooled servers, 35–45 °C, makes it suitable for recovery to heat nearby buildings. Therefore, modern data centres have a great opportunity to mitigate climate change, not only by increasing the energy efficiency of the systems thanks to the waste heat recovery for heating purposes [16], but also to save a high energy consumption of the cooling systems used to remove the heat, which accounts for 30–40% of their total energy consumption, as stated in [17].

DH is another common method of low-quality waste heat recovery that is economically viable and ecologically beneficial according to [15], in the case of using liquid cooling technologies in the data centres, which allows capturing a slightly higher quality waste heat (up to 50–70 °C). In fact, in the northern European countries with far colder winters, data centres heat recovery systems are starting to be installed to contribute to the existing DH networks in those countries. In [18], the potential for utilising waste heat from data centres in northern European countries was studied. It was concluded that, currently, the biggest challenge for the widespread use of this type of installations is not the technical problems, but the lack of clear business models for data centre operators on how to sell the waste heat to DH companies. Additionally, another barrier is the lack of available data on real energy consumption and waste heat production from data centre operators. This problem also exists but is less in the case of the present research work, as the UPV is the owner of the building and the electricity consumption of all buildings on campus is monitored. So real data is available, albeit incomplete.

In the case of the Mediterranean countries, such as Spain, with a milder a climate, the use of waste heat generated in data centres might not be so cost-effective. Indeed, the heating needs only occur during a few months in the year (October to March), and there are strong cooling needs in summer. In this case, the use of adsorption cooling would be highly convenient. However, the required temperature in the absorption unit generator is at least 70 °C, like the systems studied in [19] and [20]. In those proposals, the use of waste heat from data centres to drive a 10-ton single-effect lithium bromide-water absorption refrigeration unit was studied. These temperatures above 70 °C could be obtained in water cooled or two-phase cooled data centres, but not in air-cooled data centres, as pointed out in [24]. Another way to recover this waste heat during the summer could be to pre-heat the water needed for domestic hot water (DHW) production, but it usually requires a more complex piping arrangement and the use of a heat pump booster or similar back-up equipment.

Waste heat recovery from data centres not only saves energy but also reduces GHG emissions, especially if it replaces a fossil-fuel based heat production. In [21] the implications were analysed of abandoning coal in the DH system of Espoo (Finland), and the possibilities for waste heat from data centre to provide a cost-effective external heat source to the system. It was concluded the city's goal of 85% of heat production from carbon neutral sources could be achieved by combining the use of renewable fuels and waste heat sources (sewage water and waste heat from data centres). In addition, the increase of annual production costs was also avoided. At UPV, there is a potential application for heat recovery wherever i) cooling systems collect and dispose of heat from buildings or processes, and ii) at the same time there is a need to produce heat at temperatures lower than 80 °C [22]. This overlap will vary with the nature of facilities and their climate [23]. However, the advantages introduced by using any of these overlaps become a major tool for energy conservation and GHG reduction [24].

Also, at the UPV, improvements and refurbishments have been conducted in various buildings over the years. However, apart from the reduction of energy consumption thanks to improvements in enclosures and the use of LEDs, special focus ought to be paid to a more efficient use of energy, as well as to reducing the consumption of fossil fuels for heating on campus. Furthermore, in centralized campuses, such as UPV, with large centralized production systems, interoperability between buildings could be achieved so that they exchange energy and maximise efficiency [25]. Unfortunately, this is not the case in most Mediterranean universities and cities because they were not designed that way. The mild climate and the lack of better financial resources and environmental awareness led to solutions based on individual energy systems [26].

Looking at similar initiatives carried out at university campuses, the SESI (Stanford Energy System Innovations [27]) program action plan stands out. Its main source of generation was a natural gas-fired cogeneration plant used to power the entire campus since 1987. Stanford University discovered that, during most of the year, there were simultaneous demands for cooling and heating in its facilities. It therefore proposed the use of heat pumps to simultaneously supply these cooling and heating demands, leaving aside the cogeneration plant, which generated 90% of the university's GHG emissions, and installing a photovoltaic plant that supplies 50% of the university's electricity demand. Thanks to this project, Stanford University estimates that its campus GHG emissions will be reduced by up to 60%.

To the knowledge of the authors, there are no previous studies trying to implement the previously mentioned SESI system on a Mediterranean university campus, with mild winters and hot summers. The adaptation of the concept and its implementation into the UPV campus, will serve as a pilot for the actions planned in the city of Valencia, in the logic of energy efficiency first and renewable generation later. Also, it could be applied to all university campuses and other urban areas with similar conditions [28,29].

Therefore, this research work encompasses three main objectives pertaining to the decarbonization of the Vera campus. Firstly, to apply the SESI project approach on a Mediterranean university campus, starting with a demonstrator. Secondly, to develop a method that allows the sizing of all the necessary facilities, based on the analysis of raw experimental data, also calculating the energy savings and the reduction of GHG emissions. Thirdly, testing the great potential of waste heat from data centres, state-of-the-art heat pumps and the interoperability of buildings energy management. Besides the adaptation of the SESI project to a Mediterranean campus, the main innovations of this research work are to put forward solutions to address the issue of missing or uncertain energy data, to propose how to connect different buildings to optimize heat flows (using interoperability), and to calculate the energy savings and greenhouse gas emissions reduction resulting from the utilization of waste heat from data centres, and the simultaneous production of cooling and heating through heat pumps. This situation is similar in many other campuses and cities in the Mediterranean countries.

2. Materials and methods

One of the challenges of the present research work is to stablish a process that allowed the proposal of a more efficient energy system to help the decarbonization of the Vera campus of UPV. This involves not only the reduction of the total energy consumption of the campus buildings but also the reduction of the consumption of fossil fuels. For this purpose, a six-step method is carried out, as indicated in the flow diagram in Fig. 1.

First, a comprehensive analysis of the Vera campus of UPV is carried out, which involves examining the different schools, buildings and services that are part of the campus, analysing the energy consumption patterns on campus and, finally, identifying the data centre with almost constant cooling demand throughout the year.

During this stage, the available relevant information of the UPV campus is collected. This information includes types of heating and cooling systems used in the different buildings, shared installations, how the energy consumption of these systems is monitored, how the systems themselves are monitored, and the like. This results in the registration of a list of systems and the available data for them.

This first step identifies potential simultaneous demands of cooling and heating in different buildings of the campus: the aforementioned data centre and other nearby buildings that require either heating or cooling depending on the season. Then the cooling demand of the data centre is determined from the measured electrical power consumption. These measurements are registered every 15 min with a power meter (A2000 Multifunctional Power Meter by Gossen Metrawatt, with an error margin of 0.5% of the nominal value + 1 digit). These electrical values are then translated into cooling demand by means of the available catalogue data for the chiller. All this process is performed by a Python algorithm that uses the electrical energy consumption and the outlet temperature as inputs to estimate the cooling demand of the data centre.

Once the cooling demand of the data centre along the year is determined, a commercial water to water heat pump is selected to meet this demand. Then, the waste heat produced at different temperature levels is determined using the Coefficient of performance (COP, i.e. the ratio between the heating capacity of the heat pump and its electrical power consumption) of the heat pump for these conditions as a conversion factor.

The 4th step of the process consisted of the selection of the buildings that are going to use the waste heat generated by the data centre. In this case the main criterium, jointly with the fact that the buildings are being heated by the central gas boilers of UPV, is their proximity to the data centre. The main motivation for that relied on two objectives, the first one to have a system as simple as possible, and the second one to evaluate the potential use of this heat in the most commonly used buildings in a university located in a Mediterranean area: typically, classrooms and offices. In this way, the potential use of these strategies in less favourable conditions, such as buildings with high internal loads in mild climates can be determined. In addition, universities should have heating demands in singular installations like swimming pools, greenhouses or specific laboratories. In cases where the heat production exceeds the demand of the main buildings, it can be used in these other specific premises. In this research work, some greenhouses, not far away from the data centre, are selected as complementary buildings to absorb all the waste heat produced.

The next step is to determine the heating demand of the selected buildings. Unfortunately, in most cases, this information is not readily available. In this case study, the total electric consumption is registered but the heating demand is satisfied by a central gas boiler system, and it is not possible to determine the real heating demand due to the lack of experimental data. To overcome this limitation, a building model is developed for each building using the building simulation software CYPETHERM HE Plus. This software is developed by a Spanish company for energy certification of buildings and is based on Energy Plus software for building simulations [30]. The model included information regarding the geometry, construction materials, use, internal loads, temperature setpoints for the air conditioning systems and the like. The values to define the internal loads and uses are based on the standard values defined by the Spanish regulation [31].

This model is validated in cooling mode with the measured electrical energy consumption of the building during summertime and, based on that, the heating demand in winter is estimated. Once the waste heat production and the heating demand are determined, a thermal energy storage system must be sized to help a better balance of the thermal loads generated in the data centre and those demanded for heating in the selected nearby buildings. For a full discussion on this, see [32]. Eq. (1) is considered to size the storage system:

$$Q = \rho^{*}V^{*}Cp^{*}\Delta T \quad (1)$$

Where:

ρ: Density of water.
V: Volume of the tank.

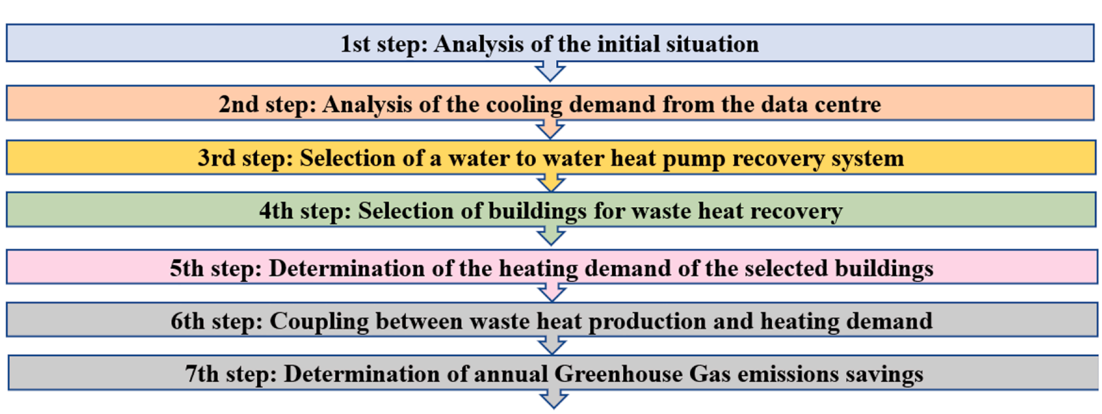

Fig. 1. Steps followed in the research work.

Cp: is the specific heat of water: 4.18 kJ/kgK.
Q: is the total heat needed to be stored in the tank.
ΔT: is the temperature difference between the water entering and leaving the tank.

The thermal energy storage is designed to cover the peak heating loads that occur in the selected buildings during the first morning hours, when the instantaneous heating demand exceeds the recoverable heat from the data centre. For the sizing of the storage volume, the hourly thermal balance for a typical day in January is analysed. This month is selected because it represents the period with the highest heating demand at UPV.

Finally, three scenarios are considered to calculate the annual GHG emissions savings thanks to the waste heat recovery system: the first scenario involves partial recovery of waste heat, the second scenario assumes complete recovery of waste heat during the heating season, and the third scenario considers full recovery of waste heat during the heating and cooling seasons using the auxiliary buildings. A conversion factor of 0.252 kg CO_2e/kWh of final energy is considered for natural gas consumption. This conversion factor is extracted from information provided by the Spanish Ministry of Industry, Energy and Tourism in [33].

3. Results and discussion

This section presents and analyses the results obtained in each of the steps followed in this research work. It should be noted that the base year considered for the calculations is 2019, in order to avoid the uncertainty of later data, deeply affected by the Covid-19 pandemic.

3.1. 1st step: Analysis of the initial situation

UPV Vera campus, founded in 1968, lies in the northeast of the city centre of València. The Vera Campus occupies an area of 558,306 m^2, with 28,801 students and 7682 employees who belong to a total of 9 technical schools and 2 faculties. Fig. 2 shows the geographical boundary of Vera Campus.

There are a total of 105 buildings on campus, mainly providing educational facilities but also services, sports facilities and greenhouses. There is also a big data centre (in building 4L located with a red frame in Fig. 2), which presents a high and almost constant cooling demand throughout the year. This data centre uses an air cooled system (chillers) that discharges excess heat into the air.

The majority of buildings were built more than 60 years ago (66%), 18% of them were constructed 40 years ago and 16% constructed within the last two decades. The average energy use of these buildings ranges from 60 to 80 kWh/m^2-year. Table 1 shows the typical overall heat transfer coefficients (U-values) of the elements of the building envelopes (e.g., walls, roofs, windows…), categorized by year of construction. Category A includes buildings from 1960 to 1979; category B from 1980 to 1999; and category C from 2000 on. This information is extracted from the TABULA webtool [34] which collects the European building materials categorized by building typology and year, as well as [35] where buildings at UPV are classified and analysed per year of construction.

The total energy consumption of Vera Campus in 2019 is 47.3 GWh, with electricity accounting for 80.2% and natural gas for 19.1%. Most of the electricity is delivered by the national grid. The total annual emissions from Vera Campus are 32,491 tons CO_2e/year. The built environment on Vera Campus stands for 39 % of the energy consumption and 46 % of GHG emissions. In particular, 18% of the total electricity consumption is used for heating, ventilation and air conditioning (HVAC) systems. The buildings have different types of HVAC systems which could be broadly classified as centralized and decentralized. There are different systems used for cooling like chillers, air handling units (AHUs) and independent systems, for heating like boilers, and independent systems. There are also reversible systems for cooling and heating such as variable refrigerant flow systems (VRF) and heat pumps. Currently, there are 25 lecture buildings and one greenhouse that use boilers for heating. In total there are 18 boilers (one operates on diesel fuel while the rest operate on natural gas) with a capacity of 18.9 MW.

The academic year runs from September to July with long breaks at Christmas and Easter. During the academic course, the opening hours of the Vera Campus are 7:00–23:00 on weekdays, 7:00–15:00 on Saturdays, and closed on Sundays.

3.2. 2nd step: Analysis of the cooling demand from the data centre

Both electrical consumption and thermal cooling consumption on a monthly basis for the UPV data centre in the year 2019 are shown in Fig. 3, along with the peak cooling loads. Electricity consumption remains consistently high throughout the year, with an average cooling demand of 138,418 kWh and a maximum of 154,484 kWh in August. Being an interior room with constant heat generation from servers, the thermal cooling demand remains constant as well. There is a slight increase in electricity consumption during summer due to rising outside temperatures, although these do not have a great influence due to the location of the room.

The data centre uses 4 chillers of the brand “Roca York Airedale”, model “DF-80AD-AT”, with a nominal cooling capacity of 69.8 kW each. The Energy Efficiency Ratio (EER), defined as the ratio of cooling capacity to compressor electrical consumption, in cooling mode is 2.47 at 35 °C outdoor temperature and a water temperature of 7 °C. The refrigerant is R407C. Without having more information about the chillers performance, the cooling demand has been based on the electrical energy consumption measured in the power meters, considering the EER. The variation in the EER has been derived from an analysis of the influence of temperature on the EER, as documented in [36], which concludes that for chillers similar to those used in the data centre, the EER increases linearly by 1.27% for each 1 °C decrease in the outdoor

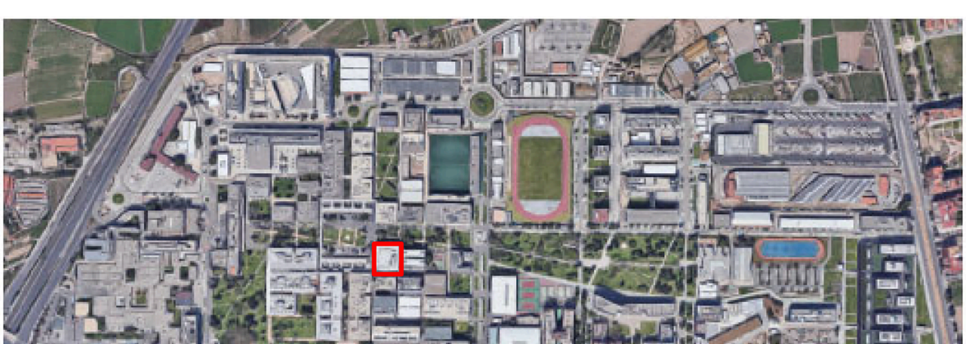

Fig. 2. Satellite image (North up) of UPV Vera Campus (Google Maps).

Table 1
U-value and thickness of the main envelope elements for buildings at UPV.

ELEMENT	EXT. WALL	ROOF	FLOOR	WINDOW
Category	A-B-C	A-B-C	A-B-C	A-B-C
U-value [W/m^2·K]	0.67–0.51–0.69	0.49–0.64–0.41	1.16–1.20–0.62	5.7–3.4–3.4
Thickness [mm]	150–285-265	0.49–0.64–0.41	390–390-610	4–12-4 all categories

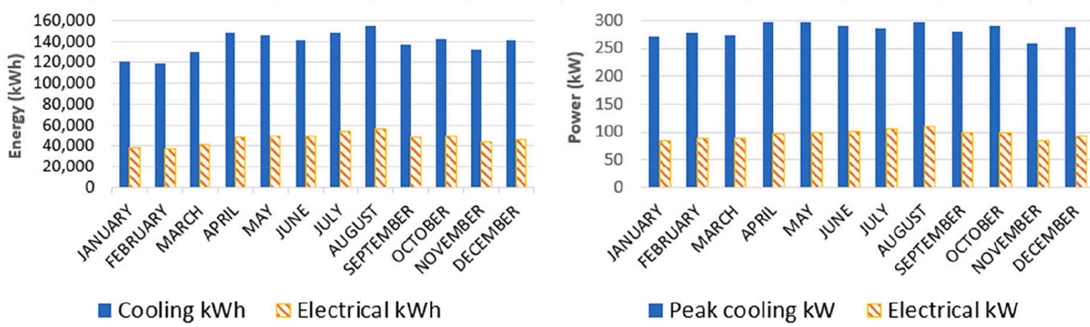

Fig. 3. Determination of the cooling thermal demand (left) and peak cooling loads at UPV data centre (right).

ambient temperature, with respect to the nominal temperature of 35 °C.

The average monthly temperature in Valencia during 2019 is obtained from climatological summaries provided by the state meteorological agency in Spain. Using both sets of data, the EER is calculated for each month, and multiplied by the monthly consumption in kWh of electricity, to obtain the cooling loads. As a result, the total yearly cooling demand is 1,661,020 kWh. The maximum peak cooling load occurs in August, reaching 297.29 kW of power. The monthly peak cooling demand is relatively constant, varying between 270 and 300 kW approximately, which underscores the stable operation of the data centre's air conditioning system. Once the heat pump recovery system is designed as per the 3rd step, it will be possible to determine the amount of waste heat that could be effectively recovered.

3.3. 3rd step: Selection of a water to water heat pump recovery system

The aim now is to replace the existing old chillers in the data centre by a more flexible and efficient equipment. Also, to use the waste heat generated in the cooling process to meet the heating demands of other nearby buildings.

3.3.1. Heat pump selection for simultaneous supply of heating and cooling

The sizing of the heat pump will be based on the cooling demand required by the UPV data centre. Considering the monthly peak cooling demand obtained in the 2nd step, the heat pump cooling capacity should exceed 297.29 kW. A search is carried out in commercial catalogues to find a model that meets the needs of the installation, and the model "NRP 1104–4 tubes - version A" from the AERMEC brand is selected. It operates with R-410A refrigerant. This heat pump has 3 different operating modes: cooling, heating, and simultaneous cooling and heating. In this case, only two working modes will be used: cooling only (299.6 kW, EER = 3.01) and simultaneous cooling (306.9 kW) and heating (392.1 kW).

In the simultaneous operation mode, for every electrical kW consumed, the heat pump can provide 7.64 thermal kW, distributed between the cold and heat supplied simultaneously. The simultaneous operation mode is intended to be active as long as it is possible to use the heat supplied in the sink. At times when there is no heat demand, or it is completely covered, it will operate in cooling only mode, evacuating the heat from the condenser to the environment through an air condenser, incorporated in the heat pump. When simultaneous consumption occurs, the heat pump operates in water-to-water mode with a heat exchanger at each focus to transfer heat from the refrigerant cycle to the water cycle; whereas when only cooling is produced, it operates as an air-to-water heat pump, with the cold focus corresponding to the water and the hot focus to the air, expelling the heat generated through the air condenser. Cold water can be produced at a temperature between 4 and 18 °C and hot water between 25 and 55 °C. Finally, it should be noted that the changeover between the two modes is automatic thanks to a microprocessor installed in the heat pump.

3.3.2. Determination of the recoverable waste heat

Once the cooling demand of data centre, expressed in kWh, has been obtained in the 2nd step, and the heat pump that will be installed has been selected, the heating kWh that the heat pump will simultaneously produce in the condenser can be obtained, considering the data from the heat pump performance catalogue. The results in Fig. 4 show that the recoverable waste heat obtained in the data centre is quite constant throughout the year, with an average value of 176,845 kWh and a total yearly recoverable heat equal to 2,122,144 kWh.

3.4. 4th step: Selection of buildings for waste heat recovery

This research work is initiated by the Technical School of Industrial Engineering (ETSII), aiming to promote the decarbonization of the campus. Hence, the buildings of ETSII located near the data centre are selected for analysis, as shown in Fig. 5 (buildings 5B to 5N). These buildings were built in the 1970s and are categorised as A according to Table 1. The UPV data centre is located in building 4L, indicated with the red frame, at the bottom of Fig. 5. Building 5Q houses the central natural gas boilers. Building 5P consists of greenhouses built in the 1990s. Building 5S comprises various stores and commercial premises. The remaining buildings are dedicated to lectures, offices, technical rooms and labs in different proportions, as depicted in Fig. 5 on the right. The chart shows also which buildings have the total electricity consumption measured by power meters, and also the air conditioning. In order to select the buildings where the data centre waste heat would be recovered, two conditions need to be fulfilled: the electricity consumption is high, and the heating is supplied with hot water coming from the gas boilers.

The total electricity and air conditioning electricity consumption expressed in kWh/m^2 are shown in Table 2, where it is also indicated for

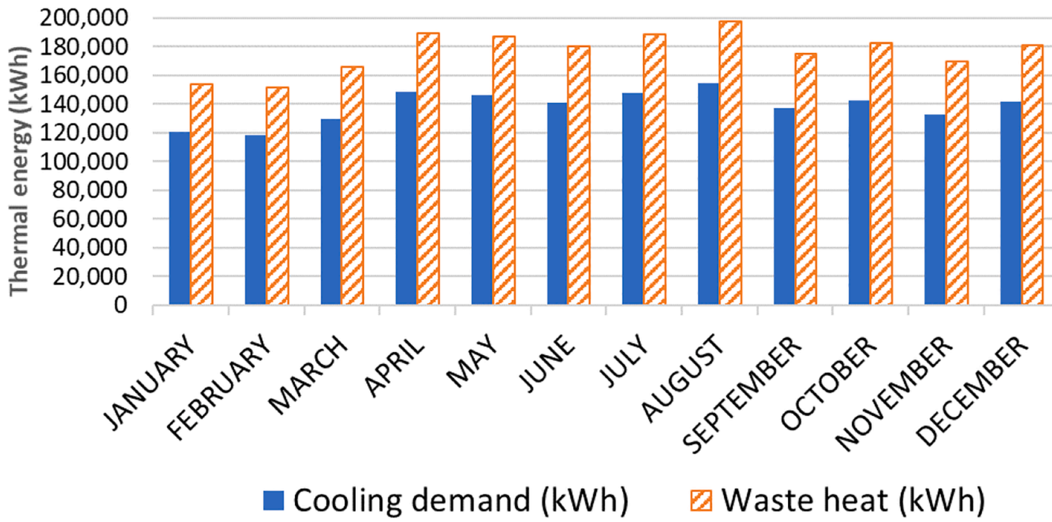

Fig. 4. Determination of the recoverable waste heat from the UPV data centre.

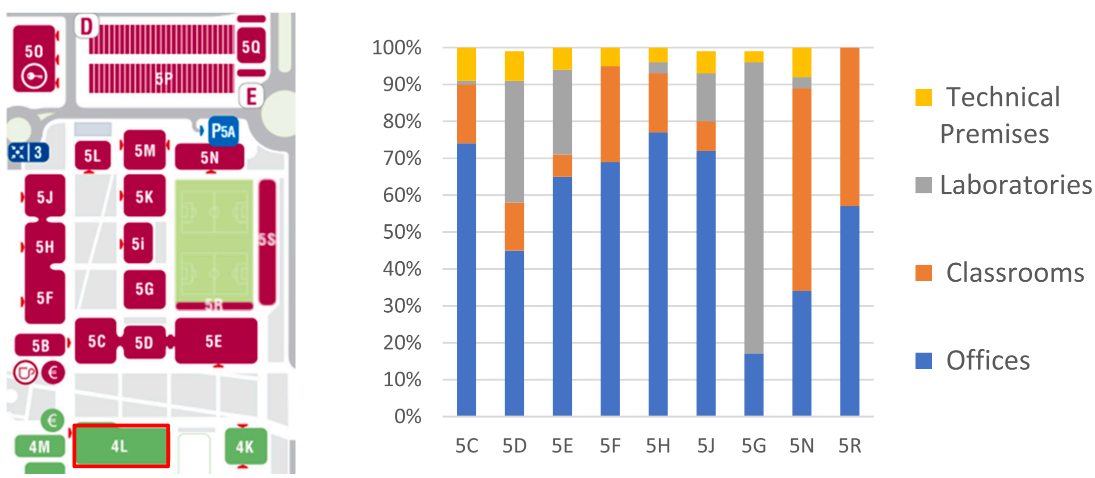

Fig. 5. Map of ETSII (left) and surroundings, and energy use ratio of ETSII buildings (right).

Table 2
Electrical energy consumption of buildings per unit area.

BUILDING	Air conditioning consumption (kWh/m^2)	Total electricity consumption (kWh/m^2)
5R	38.00	68.01
5C+5D (GAS)	29.05	45.46
5N	17.21	37.57
5E	12.49	41.10
5F+5H+5J	10.62	40.77
5G (GAS)	0.83	21.16

which of the buildings heating is covered by the gas boilers (word 'GAS' in brackets).

It should be noted that, for some of the buildings, there is no individual information measured by the power meters and it is measured in aggregate form. Looking at Table 2, the aggregation of buildings 5C-5D is finally selected as they have the second highest electricity consumption in kWh/m^2 jointly with the fact that the heating in these buildings is powered by natural gas, i.e., heating is not considered in the air conditioning consumption of the power meters, and still has a high consumption in total kWh/m^2.

Another important issue to consider is that during the night there is still cooling demanded that needs to be supplied in the data centre. However, there is no heating demand at night in the selected buildings 5C-5D as activity in most of labs, offices and classrooms is at a standstill. Therefore, it would be convenient to identify a nearby building where there is a coinciding heating demand during these night periods. Looking at the ETSII buildings shown in Fig. 5 on the left, the greenhouse building 5P would meet this selection criterion. The electricity consumption in buildings 5C-5D and 5P for the year 2019 is shown in Fig. 6.

According to Fig. 6, the total electricity consumption of buildings 5C-5D is considerably marked by air conditioning consumption. Air conditioning includes heating and cooling depending on season, and the ventilation consumption (50 kWh on average per day for buildings 5C-5D). Heating is available from November to April when boilers are switched on. Cooling operates from May to October. In April, except for specific days, ventilation alone is sufficient to maintain optimal indoor temperatures. The lowest electricity consumption occurs in March and April, when less air conditioning is required due to mild temperatures outdoors. However, the peak electricity consumption occurs in July despite there being no lectures and students. These buildings also contain laboratories and offices and the air conditioning systems continue on operation for professors and researchers. In August, there is a large drop in electricity consumption, as most facilities are closed during summer holidays with almost no students or professors on campus. September experiences again a peak in electricity consumption

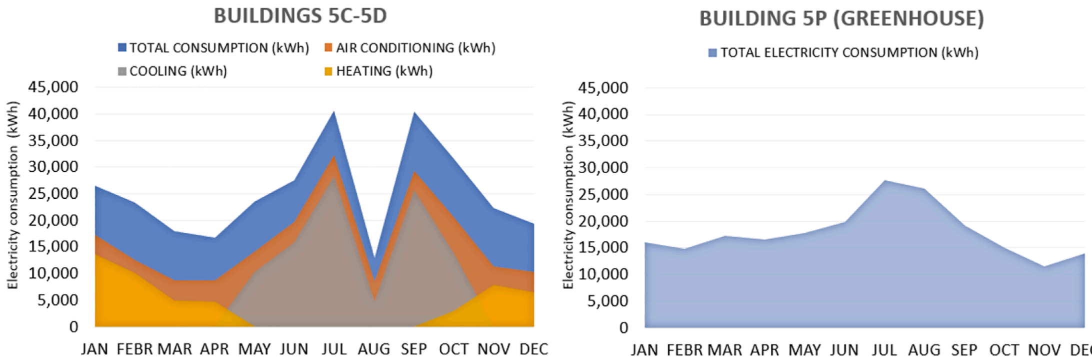

Fig. 6. Electricity consumption in the selected buildings (5C-5D left and 5P right) in year 2019.

but of lesser magnitude compared to July because temperatures are milder. During winter months, electricity consumption for heating is only due to the auxiliaries, as heating and DHW is supplied by the natural gas boilers rather than the air conditioning system. For 5P building only total electricity measurements are available.

The 5P building is a greenhouse, so the consumption in August is similar to that of July, as the facilities must continue to be refrigerated to maintain the plants in optimal conditions. This building has a total electricity consumption of 28.01 kWh/m^2 and uses hot water supplied by the central natural gas boilers for heating.

3.5. 5th step. Determination of the heating demand of the selected buildings

For this step, it will be necessary to determine the thermal heating demand of the buildings, either by reading experimental electricity consumption data or by simulating the buildings' energy use. For clarification, Fig. 7 shows an image of the buildings involved to have a better understanding of the facilities under study.

As introduced, there is no data available on electricity consumption for heating in buildings 5C-5D and 5P because it is supplied by a gas boiler, and only the total annual consumption of natural gas for UPV is available. Therefore, for calculating the heating demand of these buildings, information has been extracted from the files generated by "Energy Plus" during the simulation in CYPETHERM software. The buildings are simulated based on real information on construction, use, internal loads, etc. as detailed in [37]. To validate the model, the resulted total electrical energy consumption for cooling is compared to the calculated consumption based on the measured electricity consumption for air conditioning and the EER of the air-to-water chillers used for cooling in the buildings (obtained from the catalogue data). Fig. 8 shows the monthly thermal demand obtained from the energy simulation compared to estimated demand from electrical energy measurements for buildings 5C-5D and 5P. As no experimental data is available for heating mode, the validation could only be carried out for cooling mode.

Considering the total thermal energy demand throughout the year 2019, a deviation of 3.9% is obtained for the total cooling demand in the case of buildings 5C-5D, being 10% in building 5P. Further checking with the people working at the greenhouses 5P revealed that the HVAC system of the greenhouses is undersized as it fails to reach the set point temperature of 29 °C during the hottest periods in summer, occasionally even exceeding 35 °C. This leads to a higher energy demand calculated in the simulation software where the thermal demand is obtained for a set point temperature of 29 °C. Despite the lack of experimental measurements in heating mode, the simulation results are considered sufficiently valid for the purpose of precision in this research, i.e. the evaluation of the potential of waste heat recovery from a data centre to reduce heating loads in a Mediterranean climate.

Results obtained show that the aggregation of buildings 5C and 5D has a total thermal heating demand of 104,590 kWh throughout the year, while the greenhouses of building 5P have a demand of 291,481 kWh. Finally, Fig. 9 shows the comparison between the monthly recoverable waste heat from the UPV data centre and the monthly heating thermal demand for these buildings.

3.6. 6th step. Coupling between waste heat production and heating demand

Considering the heat being generated by the heat pump in the simultaneous production of heating and cooling required to meet the needs of the UPV data centre, the available hourly waste heat is compared with the calculated heating demands of buildings 5C-5D and 5P. At the same time, the peak heating demand in buildings 5C and 5D needs to be covered.

To show and better understand the hourly operation of the system, Fig. 10 includes an illustrative graph of how it works in a typical heating day in January. This month is selected as it represents the period with the highest heating demand at UPV, and thus presents the biggest challenges in meeting the heating demands of the selected buildings, especially during peak heating hours.

The 5th of January has been chosen as the typical day for the month as it closely resembles the monthly average in heat available from the heat pump and the heating demands of buildings 5C-5D and 5P. For this, the monthly average thermal heating demand and the monthly average waste heat are compared to the daily values of each day of the month.

Fig. 7. 3D view of buildings: 5C and 5D on the left, and 5P (greenhouses) on the right.

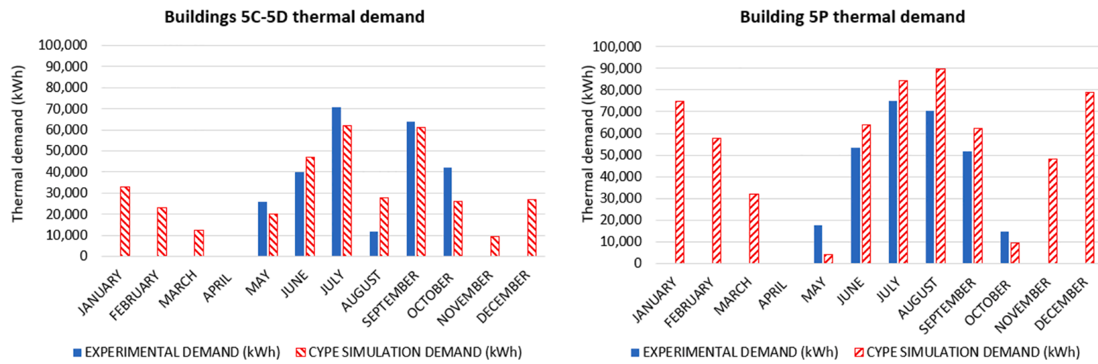

Fig. 8. Monthly thermal energy demand simulation results versus experimental measurements in the selected buildings 5C-5D (left) and 5P (right).

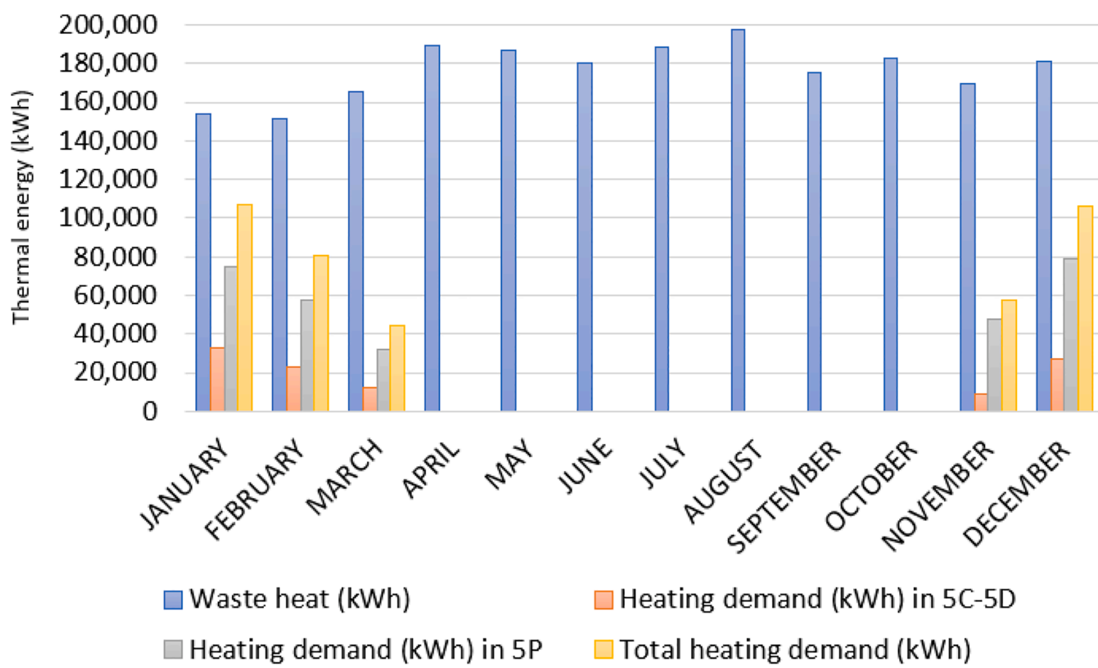

Fig. 9. Monthly comparison between recoverable waste heat from the data centre, and heating demand in the selected buildings 5C-5D and 5P.

The day whose daily values are closer to the monthly averages is selected as the typical day for the month. Fig. 11 shows this analysis where a discontinuous vertical line indicates the selected day. This will be the day considered for sizing the storage tank.

Note that all the waste heat generated by the heat pump will first be used to cover the demand of buildings 5C and 5D. When this is completely covered, the remaining recoverable waste heat will be used for the 5P greenhouses, always in that order.

Fig. 10 shows that the constant data centre waste heat during all hours becomes a problem at certain times of the day, as the heating demand is not constant in the other facilities. Indeed, it is especially higher during the peaks early morning hours, where the system would not be able to fully cover the heating demand of buildings 5C-5D. Starting the analysis at 00:00, during the night and until 08:00, the 5C-5D buildings do not require air conditioning, so all the waste heat produced during these hours can be sent to the 5P greenhouses. At peak hours, the remaining heat demanded will then be supplied by the thermal storage tanks, where their available energy covers the mismatch between the thermal demand of 5C-5D and the waste heat available from the heat pump. The same is repeated for the next 2 h until 11:00, when the demand of 5C-5D decreases below the waste heat supplied by the heat pump, the available heat in the tanks having decreased at the same time.

After that, the heat pump can supply the heating required by 5C-5D, producing a surplus heat. This will be sent to the greenhouses as long as there is demand, which is until 13:00. After that time, the remaining heat will be used to reheat the water in the thermal storage tanks. From then on, the heat pump will switch between simultaneous cooling and heating mode whenever there is a demand for heat, and cooling only mode when there is no heating demand of any kind. In cooling only mode, the cooling demand in the data centre is always covered and the heat produced in the hot source is evacuated to the environment through the air condenser incorporated in the heat pump.

3.6.1. *Sizing of the needed thermal storage*

A thermal storage system will be sized in this step. Water will be used to store the thermal energy, as it is readily available on campus, inexpensive, and has a high specific heat capacity. The sizing criteria for the inertial storage tank is based on Eq. (1), where it is considered that the tank should accumulate a total heat amount Q of 450 kWh to cover the peak demands that occur in buildings 5C-5D between 8:00 and 10:00 in the morning. This amount of heat is determined for the typical day selected of the most demanding month, 5th of January, as previously explained. In addition, a ΔT of 20 K is assumed, corresponding to an

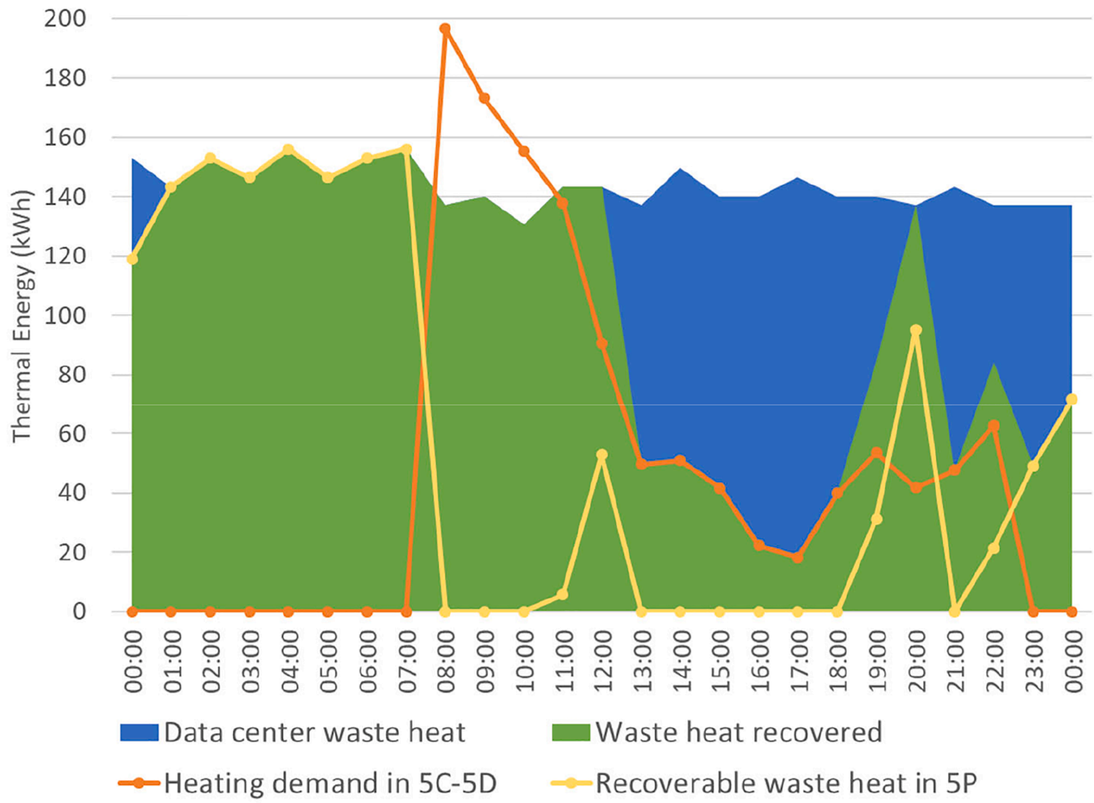

Fig. 10. Balance between waste heat produced and heat recovered on a typical heating day.

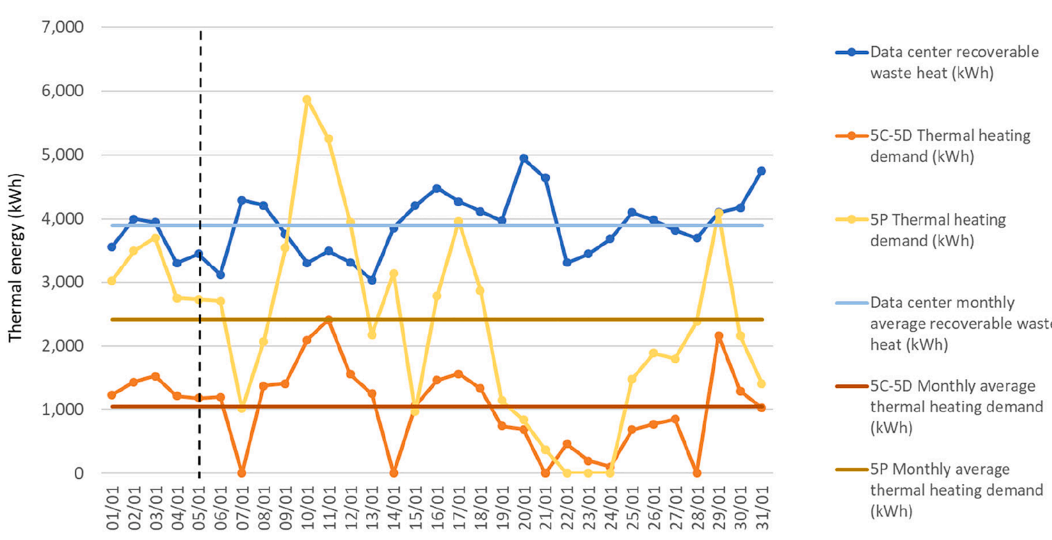

Fig. 11. Selection of the typical day in January considered for the thermal storage design.

inlet temperature of 35 °C and a water outlet temperature of 55 °C. These values are considered as the design values for the AHUs of the buildings.

As a result, one or more tanks with a total volume of 19.38 m^3 are required. After a search in commercial catalogues, four 5,000-liter inertial storage tank of the Chromagen brand, model AICV011, are selected. Considering that a total of 20 m^3 is available in the tanks, they will be capable of storing a total of 464.44 thermal kWh.

3.7. 7th step: Determination of annual GHG emissions savings.

Finally, the GHG emissions reduction obtained with the new air conditioning system has been calculated. Three different scenarios have been considered for the analysis: Scenario 1 where the waste heat from the UPV data centre is partially recovered and used to supply the heating demand of buildings 5C-5D and 5P. The natural gas savings from the boiler room in this case are 254,106 thermal kWh (64% of the buildings total demand), corresponding to 64,035 kg of CO_2e emissions saved.

Scenario 2, where the waste heat from the data centre is completely recovered and used for heating, not only in buildings 5C-5D and 5P but also in other buildings located on campus during all the heating season. The natural gas savings from the boiler room in this second case have increased to 821,964 kWh, corresponding to 207,135 kg of CO_2e emissions saved.

And finally, Scenario 3, where all the waste heat generated in the data centre would be recovered also during the summer season (from April to October), where the hot water from the heat pump condenser could be used in other installations such as the swimming pool located on the campus (it must be heated all year round), or to cover the domestic hot water needs during those months. This last scenario could result in a total of 2,122,144 kWh of recovered thermal energy and 534,780 kg of CO_2e emissions saved. However, after checking internally with the UPV infrastructure service, systemic changes in the facilities would be needed for the second scenario, and specially for the third one, so they are not currently feasible. Therefore, for this case study, the application of the method results in proposing Scenario 1 as a pilot project to be implemented in the short-medium term in the buildings 5C-5D and greenhouses in building 5P. This will serve as an example of good practice that can be replicated in the long term in different buildings and applications on campus, or the city of Valencia.

4. Conclusions

This research work presents a method for adapting the SESI program to the conditions of university campuses in Mediterranean climate cities. For this, it evaluates the potential of residual heat from data centres to reduce the demand for heating in university buildings, and therefore the demand for non-renewable fuels and their corresponding GHG emissions. All of this is in the context of a strong commitment to decarbonize the built environment.

The method uses available data from monitoring and management systems, as well as potential experiments. In addition, the method completes data when they do not exist, are not adequately disaggregated, or are uncertain. The data correspond to different buildings with varying heat and/or cooling demands that do not match into their seasonal variation or hourly profile. In this article, solutions have been proposed to address these mismatches and maximize the utilization of residual heat. This promotes the interaction between buildings and central services, building smart district solutions.

The technology that makes all of this possible is a combination of heat pumps that can supply both heat and cooling simultaneously or separately, intelligent systems that read the flows of residual and demanded heat and manage the heat pumps, heat exchangers, and transportation systems to deliver what is needed to each building, and a thermal energy storage system to address mismatches. This system allows for cooling of the data centre servers, covering the demand for heating and domestic hot water with residual heat, and completely replacing the natural gas boiler system that has been used until now.

The case study of the ETSII buildings at UPV in Valencia, Spain, has been used, including a large data centre, two large buildings with classrooms, faculty offices and laboratories, and a greenhouse complex. Three scenarios have been considered, and even in the most conservative one, energy savings exceed 60%. As found in other scientific publications, barriers to the utilization of waste heat are not technical. On the contrary, what most hinders the implementation of these solutions is the lack of data, individualized and uncoordinated energy management of buildings, aversion to construction and changes, and lastly, lack of awareness of the true potential of methods such as the one presented here, or of the waste heat from data centres. This study aims to help overcome most of these barriers.

The simulations do not consider losses of the heat exchangers and heat transport between different buildings. However, the results demonstrate the great potential of utilising this waste heat. In the coming months, the demonstrator project will be completed with these elements, but no significant variations are expected. In addition, an economic analysis will be included to calculate the capital expenditure, operational expenditure, and payback period for this investment. The benefits of combining these measures with the incipient electricity generation projects through photovoltaic panels to be carried out at the UPV will also be tested. It remains for future analysis the use of climate files that forecast the impact of climate change, such as the weather in 2030, to calculate how longer and hotter summers, as well as shorter and milder winters, may affect the system's performance.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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References

[1] European C. The European Green Deal 2019. https://ec.europa.eu/commission/presscorner/detail/en/ip_19_6691 (accessed May 1, 2022).
[2] European C. Proposed Mission: 100 Climate-neutral Cities by 2030 – by and for the Citizens 2022. https://research-and-innovation.ec.europa.eu/funding/funding-opportunities/funding-programmes-and-open-calls/horizon-europe/eu-missions-horizon-europe/climate-neutral-and-smart-cities_en (accessed May 1, 2022).
[3] Amaral AR, Rodrigues E, Gaspar AR, Gomes Á. A review of empirical data of sustainability initiatives in university campus operations. J Clean Prod 2020;250:119558. https://doi.org/10.1016/j.jclepro.2019.119558.
[4] Emeakaroha A, Ang CS, Yan Y. Challenges in Improving Energy Efficiency in a University Campus Through the Application of Persuasive Technology and Smart Sensors. Challenges 2012;3:290–318. https://doi.org/10.3390/challe3020290.
[5] Gomes Ricardo, Pombeiro H, SC, CP, CM, AG, DP, FP. Towards a Smart Campus: Building-User Learning Interaction for Energy Efficiency, the Lisbon Case Study. In: Leal Filho Walter, Brandli L, CP, NJ, editor. Handbook of Theory and Practice of Sustainable Development in Higher Education : Volume 1, Cham: Springer International Publishing, 2017, pp. 381–98. 10.1007/978-3-319-47868-5_24.
[6] Dvorak V, Zavrel V, Torrens Galdiz JI, Hensen JLM. Simulation-based assessment of data center waste heat utilization using aquifer thermal energy storage of a university campus. Build Simul 2020;13:823–36. https://doi.org/10.1007/s12273-020-0629-y.
[7] European parliament. Promotion of the use of energy from renewable sources. Strasbourg; 2018.
[8] van de Bor DM, Infante Ferreira CA, Kiss AA. Low grade waste heat recovery using heat pumps and power cycles. Energy 2015;89:864–73. https://doi.org/10.1016/j.energy.2015.06.030.
[9] Ommen T, Thorsen JE, Markussen WB, Elmegaard B. Performance of ultra low temperature district heating systems with utility plant and booster heat pumps. Energy 2017;137:544–55. https://doi.org/10.1016/j.energy.2017.05.165.
[10] Østergaard PA, Andersen AN. Economic feasibility of booster heat pumps in heat pump-based district heating systems. Energy 2018;155:921–9. https://doi.org/10.1016/j.energy.2018.05.076.
[11] Lumbreras Mugaguren M, Garay Martínez R, Sánchez Zabala V, Korsholm Østergaard K, Caramaschi M. Triple function substation and high-efficiency micro booster heat pump for Ultra Low Temperature District Heating. IOP Conf Ser Mater Sci Eng 2019;609:52008. https://doi.org/10.1088/1757-899X/609/5/052008.
[12] Lund H, Østergaard PA, Chang M, Werner S, Svendsen S, Sorknæs P, et al. The status of 4th generation district heating: Research and results. Energy 2018;164:147–59. https://doi.org/10.1016/j.energy.2018.08.206.
[13] Oltmanns J, Sauerwein D, Dammel F, Stephan P, Kuhn C. Potential for waste heat utilization of hot-water-cooled data centers: A case study. Energy Sci Eng 2020;8:1793–810. https://doi.org/10.1002/ese3.633.
[14] Lu T, Lü X, Remes M, Viljanen M. Investigation of air management and energy performance in a data center in Finland: Case study. Energy Build 2011;43:3360–72. https://doi.org/10.1016/j.enbuild.2011.08.034.
[15] Ebrahimi K, Jones GF, Fleischer AS. A review of data center cooling technology, operating conditions and the corresponding low-grade waste heat recovery opportunities. Renew Sustain Energy Rev 2014;31:622–38. https://doi.org/10.1016/j.rser.2013.12.007.

[16] Deymi-Dashtebayaz M, Valipour-Namanlo S. Thermoeconomic and environmental feasibility of waste heat recovery of a data center using air source heat pump. J Clean Prod 2019;219:117–26. https://doi.org/10.1016/j.jclepro.2019.02.061.

[17] Rong H, Zhang H, Xiao S, Li C, Hu C. Optimizing energy consumption for data centers. Renew Sustain Energy Rev 2016;58:674–91. https://doi.org/10.1016/j.rser.2015.12.283.

[18] Wahlroos M, Pärssinen M, Rinne S, Syri S, Manner J. Future views on waste heat utilization – Case of data centers in Northern Europe. Renew Sustain Energy Rev 2018;82:1749–64. https://doi.org/10.1016/j.rser.2017.10.058.

[19] Haywood A, Sherbeck J, Phelan P, Varsamopoulos G, Gupta SKS. Thermodynamic feasibility of harvesting data center waste heat to drive an absorption chiller. Energy Convers Manag 2012;58:26–34. https://doi.org/10.1016/j.enconman.2011.12.017.

[20] Haywood A, Sherbeck J, Phelan P, Varsamopoulos G, Gupta SKS. A sustainable data center with heat-activated cooling. 2010 12th IEEE Intersociety Conference on Thermal and Thermomechanical Phenomena in Electronic Systems, ITherm 2010; 2010. 10.1109/ITHERM.2010.5501334.

[21] Hiltunen P, Syri S. Low-temperature waste heat enabling abandoning coal in Espoo district heating system. Energy 2021:231. https://doi.org/10.1016/j.energy.2021.120916.

[22] Zhang C, Luo H, Wang Z. An economic analysis of waste heat recovery and utilization in data centers considering environmental benefits. Sustain Prod Consum 2022;31:127–38. https://doi.org/10.1016/j.spc.2022.02.006.

[23] Li H, Hou J, Nord N. Using Thermal Storages To Solve the Mismatch Between Waste Heat Feed-in and Heat Demand : a Case Study of a District Heating System of. Int Conf Appl Energy 2019;2019:1–5.

[24] Wheatcroft E, Wynn H, Lygnerud K, Bonvicini G, Leonte D. The Role of Low Temperature Waste Heat Recovery in Achieving 2050 Goals: A Policy Positioning Paper. Energies (Basel) 2020:13. https://doi.org/10.3390/en13082107.

[25] Kim H, Choi H, Kang H, An J, Yeom S, Hong T. A systematic review of the smart energy conservation system: From smart homes to sustainable smart cities. Renew Sustain Energy Rev 2021;140:110755. https://doi.org/10.1016/j.rser.2021.110755.

[26] Masip X, Prades-Gil C, Navarro-Peris E, Corberán JM. Evaluation of the potential energy savings of a centralized booster heat pump in front of conventional alternatives. Smart Energy 2021;4:100056. https://doi.org/10.1016/j.segy.2021.100056.

[27] Stanford University. Stanford University: Energy and Climate Plan, 2015; 2015. https://sustainable.stanford.edu/sites (accessed May 5, 2022).

[28] Huang P, Copertaro B, Zhang X, Shen J, Löfgren I, Rönnelid M, et al. A review of data centers as prosumers in district energy systems: Renewable energy integration and waste heat reuse for district heating. Appl Energy 2020;258:114109. https://doi.org/10.1016/j.apenergy.2019.114109.

[29] Guerrieri M, La Gennusa M, Peri G, Rizzo G, Scaccianoce G. University campuses as small-scale models of cities: Quantitative assessment of a low carbon transition path. Renew Sustain Energy Rev 2019;113:109263. https://doi.org/10.1016/j.rser.2019.109263.

[30] CYPE. CYPETherm HE Plus 2022. https://info.cype.com/es/software/cypetherm-he-plus/ (accessed May 5, 2022).

[31] Spain. Ministry of Public Works. Technical conditions of the procedures for the evaluation of the energy efficiency of buildings; 2020.

[32] Li H, Hou J, Hong T, Ding Y, Nord N. Energy, economic, and environmental analysis of integration of thermal energy storage into district heating systems using waste heat from data centres. Energy 2021;219:119582. https://doi.org/10.1016/j.energy.2020.119582.

[33] Ministry of Industry. CO2 emission factors and step coefficients to primary energy from different final energy sources consumed in the building sector in Spain (in Spanish); 2016.

[34] IEE Project TABULA. Typology Approach for Building Stock Energy Assessment WebTool. 2012 n.d. https://webtool.building-typology.eu/#bm (accessed May 24, 2022).

[35] Tandazo Albán AE. Arquitectura energética en los edificios del Campus de Vera de la Universitat Politècnica de València. Universitat Politècnica de València; 2020. Msc Thesis.

[36] Martínez NR. Estudio de eficiencia de plantas enfriadoras para climatización. University of Sevilla; 2007. Msc. Thesis.

[37] Labrador AP. Análisis energético y propuesta de un sistema innovador de suministro de energía térmica para la descarbonización del campus de Vera. Universitat Politècnica de València; 2021. MSc Thesis.