Enhancing Energy Transition on Campus: Implementing Thermal Accumulation Mechanisms for Flexibility

Pere A. Bibiloni[1], Jacinto Vidal[1], Vincent Canals[1], Yamile Diaz-Torres[1], Andreu Moià-Pol, Iván Alonso[1], Benito Mas[2] and Victor Marínez-Moll[1]

[1] Energy Engineering Group at the Department of Industrial Engineering and Construction / University of Balearic Islands, Palma (Spain)

[2] Technical and Infrastructure Service of the University of Balearic Islands, Palma (Spain)

Abstract

The University of the Balearic Islands has committed to reducing carbon emissions by 50% by 2030 and achieving net-zero emissions by 2050 through the United Nations' Race to Zero campaign. The UIB has developed a comprehensive strategy to enhance energy efficiency, electrify demand, and deploy 7.1 MW_p photovoltaic installations covering 113% of the campus's annual electricity consumption. The campus aims to minimize the excess hourly photovoltaic generation fed back into the distribution grid by deploying a new 4^{th}-5^{th} generation hybrid DHC network, powered by an HVAC plant based on heat pumps and chillers, with a thermal capacity of 4 MW_t and a dedicated storage system. Preliminary results, after analyzing multiple configurations of thermal energy storage systems for the HVAC system, demonstrate significant potential for reducing electrical surpluses through the deployment of a hybrid storage system. This system would include an 882 kWh_t thermal storage buffer and a 4,445 kWh_e battery storage system. The results show that the use of the proposed storage solution allows for a reduction in energy costs for cooling of between 89 to 95%, depending on the alternative considered.

Keywords: Photovoltaics, Energy Storage, Flexibility, District Heating and Cooling

1. Introduction

The European Union (EU) has established the Green Deal (Tsiropoulos et al., 2020) as a comprehensive roadmap to achieve climate neutrality by 2050, aiming to reduce greenhouse gas emissions and promote sustainable development. Decarbonization, a key focus area, seeks to reduce reliance on fossil fuels and promote renewable energy adoption. Despite traditional emphasis on sectors like manufacturing, it's crucial to recognize the role of academic institutions in this transition. The deployment of renewable energy on university campuses is essential for addressing climate change and reducing carbon emissions, providing sustainability and energy autonomy. University campuses are ideal places to install renewable infrastructure (Kalkan et al., 2011; Tu et al., 2015) such as solar panels and wind turbines, leveraging their large surface areas and available land. Although the initial construction of these systems is costly, the energy independence gained compensates for the costs over time, especially with government incentives. In this context, it's important to highlight the renewable energy projects undertaken by various universities (Elgqvist & VanGeet, 2017). Colorado State University took steps to install solar PV panels totaling 6.7MW between 2009 and 2015. At the same time, Arizona State University made significant strides by deploying both on-site (24.1 MW) and off-site (28.8 MW) solar PV panels. Additionally, across the University of California campuses, there is a collective capacity of 36 MW of solar PV panels, which contribute to generating over 52 million kWh of electricity. These initiatives demonstrate the commitment of academic institutions to transitioning towards sustainable energy sources. Additionally, it is essential to address carbon emissions related to university data centers, ensuring they come from renewable or carbon-free resources (University of Minnesota, 2023). Reducing energy consumption in institutions through the upgrade of older electrical infrastructures and implementation of more efficient systems is also crucial to making large-scale renewable energy more viable. However, ensuring the reliability of renewable energy, especially through the installation of backup systems like used generators, is important. Part of the renewable energy on university campuses can also come from carbon credits, although the primary

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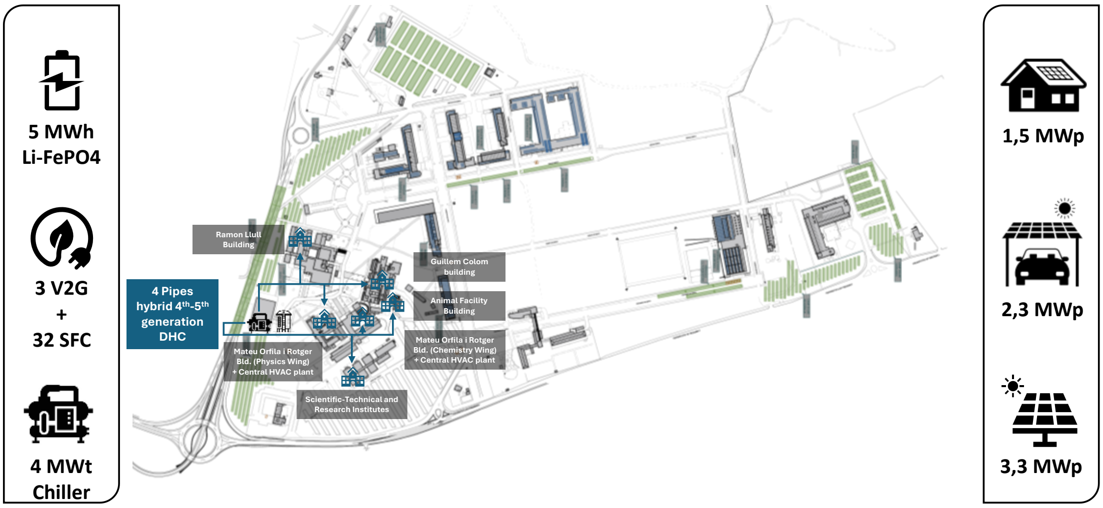

Fig. 1: Distribution of the renewable generation plants to be deployed at the UIB campus, located in Palma de Mallorca, Spain

goal should be to generate as much clean energy on-site as possible (Kiehle et al., 2023). Investing in renewable energy and carbon credits will help accelerate the transition to a more sustainable infrastructure and minimize long-term environmental impact. Furthermore, renewable energy universities are not only crucial for combating climate change but also attract future students concerned about the environment.

Due to the variable and weather-dependent nature of photovoltaic energy, integrating electric batteries is crucial to enhance self-consumption in buildings with photovoltaic systems. In the case of campuses, unused energy is stored in batteries for later use, such as during periods of low solar availability. This approach reduces dependence on both the electric grid and renewable energy sources, which are often uncontrollable and variable. Additionally, considering the price disparity between buying and selling energy to the grid, increasing self-consumption while reducing energy sales can be economically beneficial. Another strategy to improve self-consumption is to store excess energy in thermal form. If a thermal installation based on heat pumps already exists, additional components are not necessary; water tanks for energy storage and the thermal inertia of the building can be actively utilized (Zanetti et al., 2020). Some heat pump manufacturers are implementing solutions in their commercial products to boost system self-consumption. The control and optimization of integration between heat pumps and photovoltaic panels have been extensively studied in the literature (Péan et al., 2019).

The main objective of this study is to analyze, through simulations, various storage scenarios to meet the energy demand of a group of buildings on the university campus in the Balearic Islands, Spain. These buildings are interconnected through a district heating and cooling network (DHC) to serve as a flexibility mechanism and allow the valorization of photovoltaic surpluses derived from the deployment of a larges photovoltaic facilities and an electric storage system.

2. Case of study

The University of the Balearic Islands (UIB) joined the United Nations' Race to Zero campaign in 2021, committing to reduce carbon emissions by 50% by 2030 and achieve net-zero emissions by 2050. Additionally, UIB faced a significant increase in energy costs due to the Ukraine War, with energy costs rising by 281% between 2020 and 2022, reaching €3 million. In response to these challenges, UIB, with the assistance of various research groups, developed a strategy to reduce energy consumption and CO_2 emissions by improving building energy efficiency, electrifying demand, and deploying a set of photovoltaic installations to cover 113% of the campus's annual electricity consumption. Through projects developed under this strategy, UIB secured €20.8 million in competitive calls from the Mechanism for Recovery and Resilience (MRR), part of the EU's Next Generation EU funds aimed at supporting investment and reforms in Member States for sustainable and resilient recovery from the COVID-19 pandemic while promoting EU ecological and digital priorities.

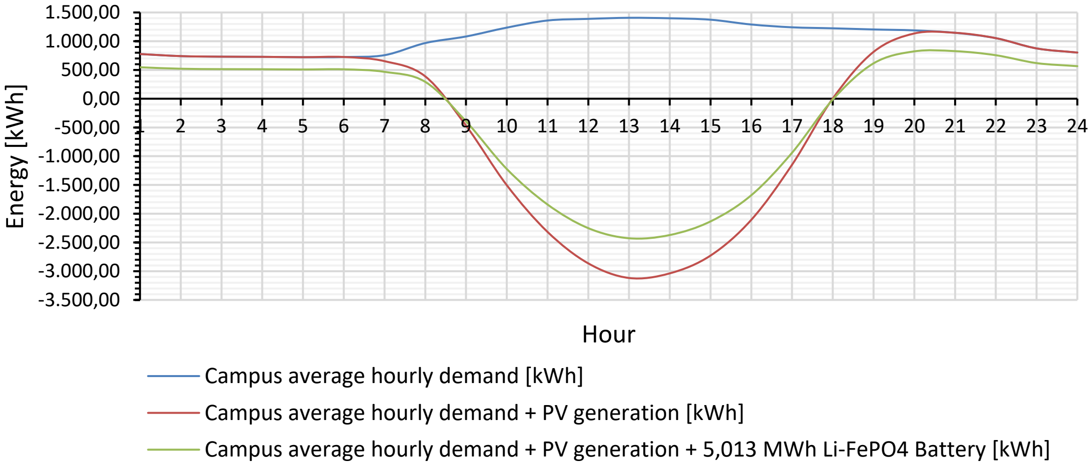

Fig. 2: Average hourly baseline curve of the energy demand at the UIB campus for different scenarios of photovoltaic and electric storage deployment.

Currently, 0.28 MWp of the projected 7.1 MWp of photovoltaic generation has been installed on campus in 18 locations. Fig. 1 illustrates PV plants distribution. Managing photovoltaic generation will require the deployment of demand management strategies and electric storage systems, as the campus's hourly demand varies widely between 0.75 MWh and 1.4 MWh, Fig. 2 blue line, peaking at 3 MWh. Furthermore, the campus's medium-voltage evacuation line is limited to 3 MW by the Distribution System Operator (DSO), leading simulations to predict that 37.5% of generation hours will result in surpluses exceeding 3 MWh, Fig. 2 red line. To address this issue, using hourly simulations of the expected photovoltaic generation and the actual campus demands across different years, it has been determined that deploying 5.3 MWh of Li-FePO4 batteries would reduce the annual hours with generation surpluses above 3 MWh to just 7.5%. Additionally, the campus has a thermal demand of over 10 MWt, with 5 of the 15 campus buildings connected to a 3rd generation district heating and cooling network supplied by a natural gas cogeneration plant located at 1.4 km in the "Parc Bit" technology park, Palma of Majorca, Spain, adjacent to the campus.

To address the remaining 7.5% of generation hours with surpluses exceeding 3 MW, the campus will need to self-limit its generation. To tackle this issue and considering that 60% of the campus's energy demand comes from air conditioning, this study analyzes the potential flexibility that would be provided by deploying a new HVAC plant with a capacity of at least 4 MW_t, using 4-pipe heat pumps capable of producing heating and cooling simultaneously. Accompanied by a storage system designed to operate on daily charge/discharge cycles, yet to be determined by this study, to supply 6 buildings to be interconnected in a new hybrid 4th – 5th generation DHC network to be deployed, Fig. 1. This plant will act as a manageable load for the generation/demand management. It is worth noting that UIB has recently secured an additional €3.6 million for the deployment of this new plant, thermal storage systems, and the new district network (Fig. 1).

3. Materials and Methods

The methodology developed for this work to optimize the storage deployment in the preliminary design of a 4th–5th generation hybrid DHC network is carried out in three phases. The first phase focuses on synthetically determining the HVAC demand of the buildings to be interconnected to a DHC network through thermal simulations using Energy Plus. The second phase involves analyzing and optimizing various storage solutions (both thermal and electrical) from a techno-economic perspective, with the aim of maximizing the use of excess photovoltaic generation for thermal energy production while minimizing the amount of energy fed back into the electrical grid. The third phase involves analyzing the operating costs of the storage configurations when they are running optimally, to determine the true operating expenses for each setup. This analysis goes beyond simply assessing whether the configurations can fully meet the HVAC demand with energy stored from excess photovoltaic generation; it also considers the deployment costs of the various configurations. It should be noted that this analysis does not consider the implementation costs of the different storage solutions to be deployed.

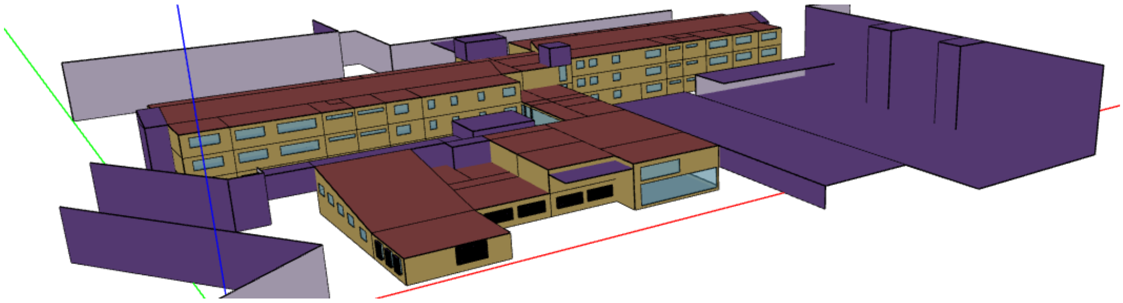

Fig. 3: 3D EnegyPlus model of the chemistry wing of the Mateu Orfila i Rotger building is created using OpenStudio.

The details of each of the three phases of the methodology are presented below.

3.1. HVAC Demand

Analyzing the energy consumption of buildings is a complex task that requires careful consideration of the interactions between the building itself, the HVAC system, and the surrounding environment. This process also involves developing effective mathematical and physical models for each of these elements. The dynamic nature of weather conditions, building operations, and the presence of multiple variables make computer-assisted design and operation essential for achieving high-performance buildings.

EnergyPlus (DOE, 2017), the official building simulation program of the United States Department of Energy, is widely used for energy simulation, load calculation, building performance analysis, energy efficiency, thermal balance, and mass balance. This program incorporates the best features of BLAST and DOE-2, along with new functionalities. It is capable of modeling heating, cooling, lighting, ventilation, and other energy flows, as well as the demand for domestic hot water in buildings. EnergyPlus is freely available and supported by the U.S. Department of Energy. Its extensive use within the scientific and technical communities, along with its robust capabilities and resources, are the primary reasons why EnergyPlus was selected as the simulation tool for estimating the thermal energy demand in this study's buildings. Additionally, EnergyPlus has been utilized in numerous other studies to estimate building energy consumption (Fumo et al., 2010; Mendes et al., 2024).

In this initial phase of the methodology, a 3D model of the buildings is created using OpenStudio (Heidarinejad et al., 2017), a suite of software tools that supports whole-building energy modeling with EnergyPlus to determine their HVAC demand. Additionally, the surrounding buildings were included in the models to accurately simulate the shadows they cast on each other (Fig. 3). It’s important to note that each building was studied separately, as they are independent from one another, and this approach also proved to be more computationally efficient. Regarding the properties of the building enclosures, the standards established in the Spanish Building Code NBE-CT-79 (Norma Básica de la Edificación, 1979), which was in effect at the time of construction of the analyzed buildings, were considered. For renovated buildings, the information provided in the engineering project was used. The different thermal zones of the buildings were identified through site visits, during which the temperature and humidity setpoints for each controllable space were recorded. As for the schedules and occupancy of offices and classrooms, these were based on data from a typical week of use for each building. Finally, to determine the internal loads of the various spaces, site visits were conducted, and after discussions with the responsible personnel, the internal thermal loads for each space were calculated.

3.2. Storage solution

The second phase of the methodology focuses on a techno-economic evaluation of various storage solutions for the preliminary design of a 4th–5th generation hybrid DHC network. This phase focuses on determining the thermal storage system (TES) necessary to meet the HVAC demand of the buildings using excess photovoltaic generation, applying statistical methodologies for a complete charge and discharge cycle of the storage deployed. It is important to note that while a discharge cycle can extend beyond a single day, in most cases, it typically aligns with a 24-hour cycle.

Specifically, to determine the optimal size and type of thermal storage system (TES) capable of handling a broad range of scenarios, rather than focusing on extreme or rare cases where excess energy from a single charge/discharge cycle might allow for a higher discharge, a statistical approach has been chosen. All of this with the primary objective is to minimize the injection of excess photovoltaic generation into the electrical grid. The following assumptions were made:

- The storage capacity is considered unlimited.
- The plant's operation is divided into 'storage' and 'discharge' periods. Storage periods occur when there is excess electricity production from the photovoltaic system, while discharge periods occur when there is no such excess.
- Each storage period is followed by a discharge period.
- Energy stored during a 'storage' period can only be used in the next 'discharge' period.
- For each charge/discharge period, only the minimum value between the stored and discharged energy is considered.

This phase of the methodology involves determining, for a given period of the year—heating period (winter) and cooling period (summer)—the necessary storage for each complete charge and discharge cycle of the storage system. To do this, the method takes the hourly HVAC demand, obtained with EnergyPlus in the first phase of the methodology, and subtracts the potential thermal energy that could be generated with a heat pump or chiller, with a certain efficiency dependent on environmental conditions, using the excess photovoltaic generation available at that hour. The excess generated thermal energy is stored to meet the HVAC demand for the required period until net excess photovoltaic generation becomes available again. This period generally corresponds to a 24-hour cycle. However, if a day occurs without excess photovoltaic generation, this period will be extended, and consequently, the amount of thermal energy to be stored will increase to cover the thermal demand. After determining the set of charge and discharge cycles, a frequency diagram is generated based on the cycle's energy accumulated over the annual period. Finally, the most optimal storage solution is selected using the Pareto rule, based on the cumulative frequency of the cycles and the required storage energy. It should be noted that the hourly HVAC thermal demand can be met either through a thermal storage system, by using batteries that store electrical energy to generate the thermal demand with heat pumps or chillers at the time it is needed, or by hybrid solutions that combine both technologies.

3.3. Optimal operating energy cost evaluation

The third phase of the methodology focuses on determining the operating costs, based on the hourly cost of electricity that must be drawn from the grid, for a specific period of the year and a particular storage system configuration. This configuration is designed to meet HVAC demand during hours when there is no surplus photovoltaic generation. To ensure optimal performance, an optimization methodology for the hourly operation of the HVAC plant connected to the DHC network has been implemented. This phase of the methodology will be crucial in evaluating and comparing the effectiveness of the proposed storage solutions in terms of their operating costs.

Specifically, we utilized Pyomo (Hart et al., 2011), an open-source Python-based software package that offers a wide range of optimization capabilities for formulating, solving, and analyzing models. Pyomo is particularly useful for modeling structured optimization applications. It allows for the definition of general symbolic problems, the creation of specific problem instances, and the solving of these instances using both commercial and open-source solvers.

For optimizing the DHC system's operation, we modeled the heating and cooling production equipment at the central HVAC plant, which supplies the DHC network. This plant was represented as a heat pump or chiller responsible for primary production and a pump group that distributes the output through the DHC network connecting various buildings. To accomplish this, we employed Copper (Pacific Northwest National Laboratory, 2020), an open-source Python library package. Copper generates performance curves for building energy simulations, specifically designed for heating, ventilation, and air conditioning equipment. The software uses a genetic algorithm to adjust existing or aggregated performance curves to match specific design characteristics, including energy performance metrics at full and partial loads. Using Copper, we generated the performance curves for the air-to-water chiller, equipped with a variable-speed screw compressor and air-cooled condenser, based on the EnergyPlus model (entering condenser temperature). These curves follow a quadratic function, resulting in a nonlinear optimization problem. To solve a real-world nonlinear programming (NLP) problem with many variables, as in the present work, the IPOPT algorithm was used. IPOPT (Kawajir et al., 2010) is an open-source solver that efficiently handles large-scale, full-space, interior-point (or barrier) nonlinear programming problems. Subsequently, Pyomo was used to describe the optimization model for the HVAC plant and DHC, based on a cost function aimed at minimizing the monetary cost of meeting the cooling thermal demand during the specified period. The model utilizes the average hourly electricity market prices in Spain for the year 2023 as a basis.

Every optimization system begins with a set of decision variables $\tilde{x}$ (eq. 1). In our case, there are seven, which are outlined below.

$$\tilde{x} = \langle x_1, x_2, x_3, x_4, x_5, x_6, x_7 \rangle \quad \text{(eq. 1)}$$

Where:

- $x_1(t)$: Electrical energy stored in the battery system over the last evaluation period (t), measured in kWh_e.
- $x_2(t)$: Thermal energy stored in the TES over the last evaluation period (t), measured in kWh_t.
- $x_3(t)$: Electrical energy discharged from the battery system to meet the thermal demand during a period (t), measured in kWh_e.
- $x_4(t)$: Thermal energy discharged from the TES during the evaluation period (t), measured in kWht.
- $x_5(t)$: Electrical energy stored in the battery during the evaluation period (t), measured in kWhe.
- $x_6(t)$: Thermal energy stored in the TES during the evaluation period (t), measured in kWht.
- $x_7(t)$: Electrical energy discharged from the battery system to meet the pumping demand during a period (t), measured in kWh_e.

These decision variables are integrated into a defined objective function $f(\tilde{x})$ by equation (eq. 2) between hours 1 and N, which must be minimized. In our case, the function is designed to optimize the system's storage to reduce the energy operating costs of the DHC network.

$$\begin{cases} f(\tilde{x}) = \sum_{t=1}^{N} \left(P_{el}[Thermal\ demand(t) - X4(t)] + P_{el}[X2(t)] + P_{el}[Pumping(t)] - X3(t) - X7(t) \right) \cdot \mathrm{AFP}(t) \\ Minimize\ \mathrm{f}(\tilde{x}) \end{cases} \quad \text{(eq. 2)}$$

Where:

- Thermal demand(t) represents the aggregated thermal demand of the buildings connected to the DHC network during a period (t), measured in kWh_t.
- $P_{el}[x(t)]$ returns the electrical energy associated with a specific thermal demand during a period (t), measured in kWh_e.
- P_{el}[Pumping] returns the electrical energy consumed by the DHC network's pumping system during a time period (t), measured in kWh_e.
- AFP(t): Average final price of the Spanish free electricity market over a period (t), measured in €/kWh_e.

In addition, the objective function (eq.2) incorporates a set of up to 4 bounds and 10 operational rules or constraints, which are detailed below.

1. The first bound (eq. 3) limits the charge/discharge rate of the battery system and the TES during the evaluation period (t).

$$\begin{cases} x_1(t) \le 1000\ kWh_e \\ x_2(t) \le 500\ kWh_t \\ x_3(t) \le 1000\ kWh_e \\ x_4(t) \le 500\ kWh_t \\ x_7(t) \le 1000\ kWh_e \end{cases} \quad \text{(eq. 3)}$$

2. The second bound (eq. 4) is responsible for limiting the minimum and maximum capacity of the battery system during an evaluation period (t).

$$0\ kWh_e \leq x_5(t) \leq 4000\ kWh_e \quad \text{(eq. 4)}$$

Where:

- In this case, the maximum electrical storage in batteries has been set at 4 MWh_e.

3. The third bound (eq. 5) is responsible for limiting the minimum and maximum capacity of the TES during an evaluation period (t).

$$0\ kWh_t \leq x_6(t) \leq 750\ kWh_t \quad \text{(eq. 5)}$$

Where:

- In this case, the maximum thermal storage has been set at 0.75 MWh_t.

4. The fourth bound (eq. 6) states that if there are no excesses in photovoltaic generation, no energy can be stored in the battery system and/or in the TES during an evaluation period (t).

$$If\ PV_{Surplus}(t) = 0\ kWh_e \rightarrow \begin{cases} x_1(t) = 0\ kWh_t \\ x_2(t) = 0\ kWh_e \end{cases} \quad \text{(eq. 6)}$$

5. The first rule (eq. 7) states that the Li-FePO4 battery system may never discharge below the energy level accumulated in the previous evaluation period (t-1).

$$x_7(t) + x_3(t) \leq x_5(t-1) \quad \text{(eq. 7)}$$

6. The second rule (eq. 8) states that the thermal energy storage system (TES) cannot be discharged below the thermal energy accumulated in the previous evaluation period (t-1).

$$x_4(t) \leq x_6(t-1) \quad \text{(eq. 8)}$$

7. The third rule (eq. 9) limits the maximum thermal demand of the system by establishing that the HVAC thermal demand of the buildings plus the thermal energy stored in the TES must always be less than or equal to the maximum power of the HVAC equipment.

$$Thermal\ demand(t) + x_2(t) \leq power\ of\ the\ HVAC\ plant$$

- In this case, the maximum power of the HVAC plant has been set at 4 MW_{th}

8. The fourth rule (eq. 10) limits storage (thermal and electric) to the amount of energy associated with the electricity surpluses from photovoltaic generation system.

$$x_1(t) + P_{el}[x_2(t)] \leq PV_{Surplus}(t) \quad \text{(eq. 10)}$$

Where:

- $PV_{Surplus}$: Photovoltaic generation surpluses that must be fed into the distribution grid during the evaluation period (t), measured in kWh_e. These values were obtained from an hourly simulation of the installations conducted with PVSyst (Soualmia & Chenni, 2017).

9. The fifth rule (eq. 11) states that the electrical energy discharged from the battery system to meet the pumping demand must not exceed the pumping system's consumption during the evaluation period (t).

$$x_7(t) \leq P_{el}[Pumping(t)] \quad \text{(eq. 11)}$$

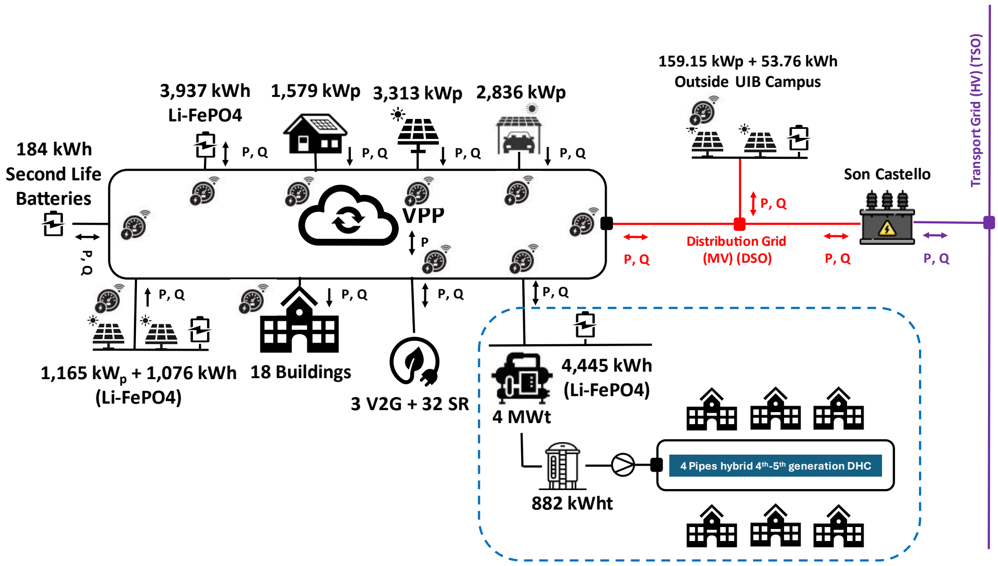

Fig. 4: Conceptual diagram of the DHC network to be implemented on the UIB campus as part of the ongoing renewable energy deployment project.

10. The sixth rule (eq. 12) is responsible for determining the state of charge of the battery system during the evaluation period (t).

$$x_5(t) = x_5(t-1) + x_1(t) \cdot 0.85 - (x_3(t) + x_7(t)) \qquad \text{(eq. 12)}$$

Where:

- The factor 0.85 corresponds to the average efficiency of the battery system.

11. The seventh rule (eq. 13) is responsible for determining the state of charge of the TES system during the evaluation period (t).

$$x_6(t) = x_6(t-1) + x_2(t) \cdot 0.85 - \frac{x_4(t)}{0.85} \qquad \text{(eq. 13)}$$

Where:

- The factor 0.85 to the average efficiency of the TES system

12. The eighth rule (eq. 14) states that the thermal energy discharged must be less than or equal to the thermal demand during an evaluation period (t).

$$x_4(t) \leq Thermal\ demand(t) \qquad \text{(eq. 14)}$$

13. The nineth rule (eq. 15) states that the battery cannot be discharged more than the electrical energy discharged from the battery to meet the electrical demand to cover the thermal demand minus the thermal energy discharged from the TES during an evaluation period (t).

$$x_3(t) \leq P_{el}[Thermal\ demand(t) - x_4(t)] \qquad \text{(eq. 15)}$$

14. The tenth rule (eq. 16) states that the electrical energy consumed from the excess photovoltaic generation must always be greater than or equal to 0 kWh_e during an evaluation period (t).

$$(P_{el}[Thermal\ demand(t) - x_4(t)] + P_{el}[x_2(t)] + P_{el}[Pumping(t)] - (x_3(t) + x_7(t)) \geq 0\ kWh_e \qquad \text{(eq. 16)}$$

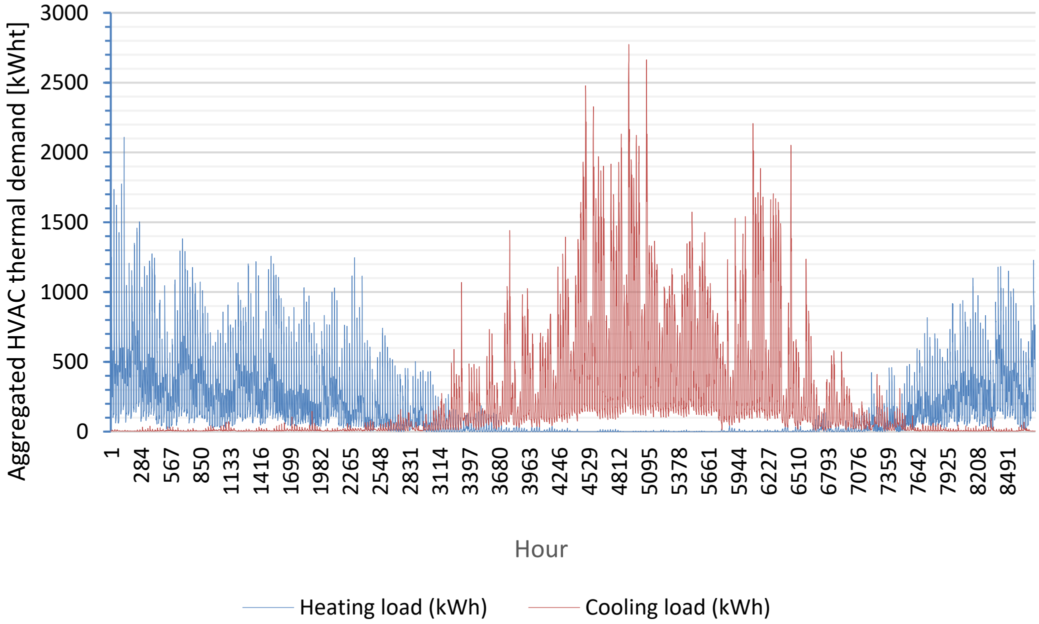

Fig. 5: Hourly total HVAC heating and cooling demand for the 6 buildings to be supplied by the 4th–5th generation hybrid DHC network being implemented.

4. Results and Discussion

In this section, we will present the results obtained by applying the methodology described in the previous section for the sizing of the preliminary design of the storage system for the 4th–5th generation hybrid DHC network, which is to be deployed on the University of the Balearic Islands campus, the case study addressed in this work (Fig. 4). It is important to note that this analysis has focused exclusively on the coverage of the cooling demand. Specifically, we will present the results obtained for the aggregated demand of the campus buildings under study. Subsequently, the procedure for the preliminary sizing of the DHC storage system to be deployed on the campus will be detailed (Fig. 4). Finally, the feasibility of the preliminary storage option chosen will be assessed based on an analysis of the annual operational energy costs, compared to the costs that would be incurred if the system were supplied by the energy service provider currently operating the existing third-generation network on campus. Additionally, the sensitivity of the proposed storage option to variations in the Coefficient of Performance (COP) and Energy Efficiency Ratio (EER) of the chillers to be installed will be examined.

4.1. HVAC Demand

This subsection presents the Energy Plus results of the aggregated heating and cooling demand for the six buildings that will be integrated into the DHC network to be deployed on the UIB campus. Specifically, Fig. 5 shows the hourly aggregated heating and cooling HVAC demand for the buildings under consideration, which include the Mateu Orfila i Rotger Building (Chemistry Wing), Mateu Orfila i Rotger Building (Physics Wing), Scientific-Technical and Research Institutes Building, Guillem Colom Casanovas Building, Animal Facility Building, and Ramon Llull Building. As illustrated in Fig. 5, the cooling demand between May 1 and October 31, 2023, ranges from 0 kWh to 2.8 MWh.

4.2. Storage solution

To determine the optimal storage capacity for the facility, based on the methodology outlined in the previous section, a frequency diagram evaluation for thermal energy storage was conducted. For this analysis, an Energy Efficiency Ratio (EER) of 2.5 was applied to the chillers converting surplus photovoltaic electricity into thermal energy, while the pumping energy consumption was estimated to account for 10% of the total HVAC electrical demand. This evaluation considers the number of complete charge and discharge cycles, which

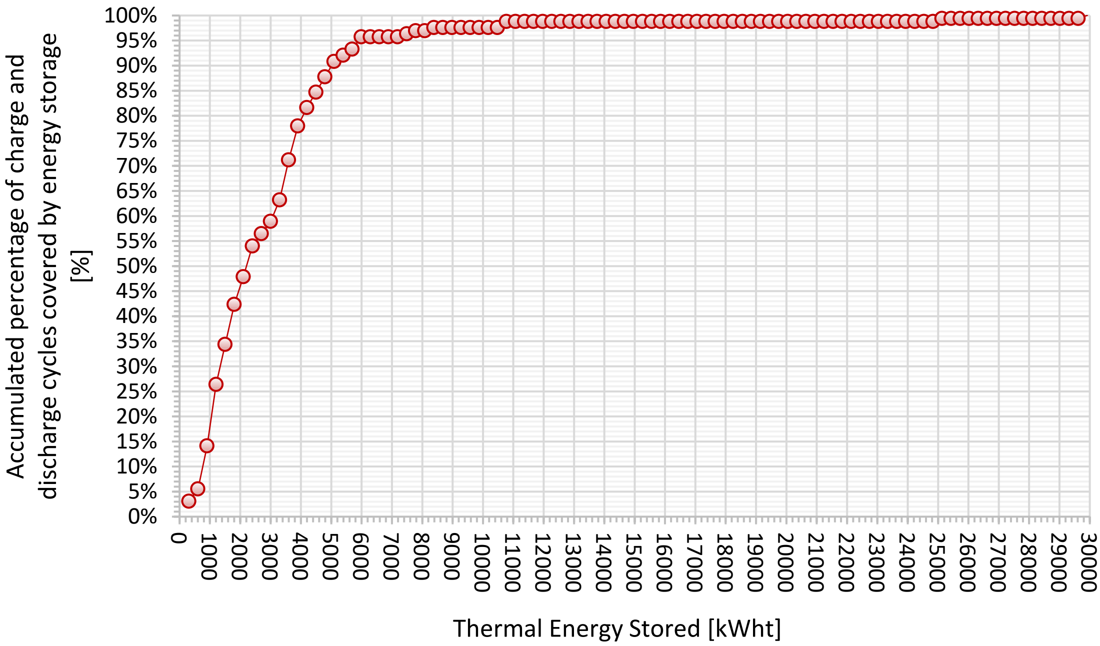

Fig. 6: Cooling thermal energy demand covered by storage during periods of net photovoltaic surpluses.

generally correspond to full days of the year when thermal storage can fulfill the entire daily cooling demand using surplus photovoltaic energy, without relying on the electricity grid. Fig. 6 illustrates this approach for meeting the hourly cooling needs of the 6 buildings that will be integrated into the DHC network.

The results in Fig. 6 indicate that with 4,000 kWh_e of thermal storage, 80% of the charge and discharge cycles for cooling the 6 buildings in 2023 would be covered. After conducting several simulations, it was determined that a hybrid storage solution, combining electrical and thermal storage, would be the most effective approach. This involves installing 4,000 kWh_e of Li-FePO4 batteries, which corresponds to a system with a storage capacity of 4,445 kWh_e, assuming a 90% depth of discharge, along with 750 kWh_t of thermal storage to serve as a buffer for the system. It's important to note that the thermal storage system was considered with an 85% depth of discharge, leading to an actual thermal storage capacity of 882 kWh_t.

This combination of 750 kWh_t of effective thermal storage and 4,000 kWh_e of electrical storage, which, with an EER of 2.5, allows for the generation of up to 10,000 kWh_t of thermal energy, can cover 98.8% of the charge and discharge cycles for cooling. Additionally, the proposed thermal storage solution on its own can cover 9.64% of the charge and discharge cycles without requiring the battery system's intervention.

Tab. 1: Sensitivity analysis of the operational energy costs for the proposed storage solution based on the chiller's EER.

Description	**Chiller with an average EER of 3.07**	**Chiller with an average EER of 3.72**	**Chiller with an everage EER of 5.17**
Electricity costs for the charge and discharge cycles not covered by the proposed storage solution:	2,725.66 €/year	2,113.04 €/year	1,454.63 €/year
Percentage reduction in electricity costs related to the storage solution, based on a reference cost of €2,725.66 per year:	0 %	22,48%	46,63%

4.3. Optimal operating energy cost evaluation

To evaluate the effectiveness of the preliminarily selected energy storage solution for the DHC network, we analyzed the energy costs associated with the charge and discharge cycles that the deployed storage system would not be able to cover. The analysis revealed that cooling costs would be as low as €2,725.66 per year, based on a chiller system with an EER of 3.07, which is a conservative estimate for this type of equipment. This cost is only around a 11% of the cost of purchasing the required electric power if there were no storage in the new DHC network and a 5% of the cost of purchasing the same thermal energy from the existing 3rd generation DHC network with an external contractor. In those cases, the forecasted costs would have been 24381,11€ and 54490,80€ respectively.

Finally, to assess the sensitivity of the operational energy costs for the selected storage solution in relation to the Energy Efficiency Ratio (EER) of the chillers to be installed, an analysis was conducted considering different EER values for the chiller while operating the proposed storage system optimally. The results are presented in Tab. 1. The results in Tab.1 demonstrate that even a slight improvement in the EER can significantly reduce electricity costs associated with cooling. However, the reduction in energy costs does not follow a linear pattern with the increase in the chiller's EER. For example, a 68.4% increase in the Chiller average EER results in only a 46.63% reduction in energy costs using the proposed storage solution.

5. Conclusions and Future Work

The UIB is actively working to position itself as a leader in sustainability and environmental management through the deployment of a photovoltaic generation facility equipped with an electric storage system. Initial results suggest that introducing demand flexibility by deploying a 4th-5th generation hybrid DHC network, powered by a highly efficient HVAC plant equipped with a thermal storage system of no less than 882 kWh_t and 4,445 kWh_e of batteries, will effectively utilize excess photovoltaic generation to meet cooling demand. This strategy would greatly reduce the amount of surplus photovoltaic energy that needs to be fed back into the distribution grid, enabling the UIB to significantly minimize its dependence on grid electricity. Additionally, the results demonstrate a substantial reduction in energy costs associated with cooling, achieving a 486.43% decrease in the most conservative EER scenario for the chillers in the central HVAC plant under the proposed storage solution.

It is important to note that the work on defining the storage solution and the topology of the 4th-5th generation hybrid DHC network to be deployed represents an initial outline of the efforts being undertaken at the UIB as part of the institutional projects PIREP and PITEIB – 1/2023. Ultimately, these projects aim to explore net-zero energy scenarios and provide insights that could serve as guiding examples for other university campuses in the Mediterranean region, facilitating significant decarbonization of their facilities through the adoption of flexibility mechanisms such as thermal and electric storage systems.

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