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Macro-scale renovation strategies to incorporate hybrid photovoltaic–heat pump systems in public residential buildings using multi-objective optimization

M. Garro-Aguilar [a,*], A. Prada [b], A. Hernandez-Arizaga [a], L.M. López-González [d], A. Picallo-Perez [c]

[a] Research group ENEDI, Department of Energy Engineering, University of the Basque Country (UPV/EHU), Alameda Urquijo, S/N, 48013, Bilbao, Vizcaya, Spain
[b] University of Trento, Dep. of Civil, Environmental and Mechanical Engineering, Trento, Italy
[c] Research group SI+E, UPV/EHU, Faculty of Engineering Gipuzkoa, Eibar, Spain
[d] University of La Rioja. (TENECO Research Group. Department of Mechanical Engineering), Spain

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ABSTRACT

The residential sector is facing a global energy transition, making energy renovation measures in building energy systems a matter of urgency. This work develops a flexible and systematic methodology to integrate photovoltaic (PV) renewable technology with heat-pump (HP) in existing installations, including electrical storage systems (EES) and thermal storage (TES), focused on 128 public rental buildings in the Basque Autonomous Community. The optimized design of these systems minimizes CO_2 emissions and energy consumption from grid and maximizes PV self-consumption. In the multi-objective optimization, installation design variables are optimized, such as the volume of the heating TES tank (V_{TES}^{heat}), and the temperature ranges in which the control intervenes.

The work presents the rehabilitation strategies of six buildings covering heterogeneous types of buildings. The optimization results show V_{TES}^{heat} values of between 6 and 9 m^3 and DHW circuit controls conditioned by health regulations. The results highlight that the dominant variable is the photovoltaic surface area available per dwelling "S_{usab}^{dw}", rather than the building size or the dwelling number, serving as a normalization parameter. It is demonstrated that, on the one hand, for higher S_{usab}^{dw} buildings, control is related to high-temperature thermal storage strategies and the use of PV surplus. On the other hand, low S_{usab}^{dw} buildings are associated with efficient HP operation strategies and smaller thermal tanks. As a result, one of the main advantages of the methodology is its replicability on a macro scale, as the optimization process is automatically adapted to each building, allowing the integration of customized energy solutions for them.

TABLE OF ABBREVIATION:

ABBREVIATION	MEANING
PV	Photovoltaic
HP	Heat-Pump
EES	Electrical Energy Storage
TES	Thermal Energy Storage
EU	European Union
TBC	Technical Building Code
BAC	Basque Autonomous Community
SH	Space Heating
DHW	Domestic Hot Water
NSGA-II	Non-dominated Sorting Genetic Algorithm-II
D_i	DHW demand at the i hour
D_p	Daily DHW demand per person
$N_{peo.}$	Number of people per dwelling
$N_{dw.}$	Number of dwellings per building.
$f_{cent.}$	Centralized factor
P_i	Percentage of the hourly profile at hour i
TES_{DHW}	Thermal Energy Storage for Domestic Hot Water supply
TES_{heat}	Thermal Energy Storage for heating supply
S_{usab}	Useable surface of the building

(continued on next page)

* Corresponding author.
E-mail address: mikel.garro@ehu.eus (M. Garro-Aguilar).

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(*continued*)

ABBREVIATION	MEANING
S_{panel}	Surface of the Photovoltaic Panel
P_{panel}^{PP}	Peak Power of the Photovoltaic Panel
f_{sec}	Security factor
V_{TES}^{DHW}	Volume of the Thermal Storage Tank for Domestic Hot Water supply
$\dot{m}_{total}$	Total daily DHW demand
V_{TES}^{heat}	Volume of the Thermal Storage Tank for heating supply
T_{heat}^{low}	Lower heating supply temperature
T_{heat}^{high}	Higher heating supply temperature
T_{DHW}^{low}	Lower Domestic Hot Water supply temperature
T_{DHW}^{high}	Higher Domestic Hot Water supply temperature
T_{Bo}^{low}	Lower Boiler supply temperature
T_{Bo}^{high}	Higher Boiler supply temperature
$kgCO_2$	Indicator for CO_2 emissions
$E_{FromGrid}^{t}$	Indicator for energy imported from the electricity grid
$f_{elec.}$	CO_2 emission factor of the electricity
Q_{boil}^{t}	Energy consumption of the boiler at each time-step
f_{NG}	CO_2 emission factor of the natural gas
$E_{PVToLoad}$	PV self-consumption increasing indicator
E_{ToLoad}^{t}	Energy derived to the HP electricity load at each time-step
WSM	Weighted Sum Method
S_{roof}	Roof Area of the Building
$\dot{Q}_{heat}^{Max}$	Maximum heating power
S_{usab}^{dw}	Useable surface of the building per dwelling

1. Introduction

The energy consumption of buildings in the European Union (EU) reaches almost 40% of global consumption [1], which highlights the urgency of promoting energy efficiency measures in this sector. In addition, considering the increasing volatility of fossil fuel prices and the rising ecological footprint of urban areas, the building sector is recognized as a key sector of the sustainable energy transition [2]. In this context, the EU has established directives [3,4] that limit energy consumption, establish energy performance ranges and regulate the environmental impact of installations.

Spain, as a member country, has transposed the directives through the Technical Building Code (TBC) [5] and, in turn, the Basque Autonomous Community (BAC) has reinforced the legislation at the regional level [6] to retrofit existing buildings in energy terms, taking into account the socio-cultural particularities of the area. In the BAC [7], as in most EU countries, half of the residential stock was built before the first thermal regulations (i.e., before 1970) [8].

As can be seen, energy retrofitting is considered a key strategy to move towards climate goals, as pursued by Sustainable Development Goals [9] 7 and 13. Thus, improving the quality of the buildings and introducing renewable energy sources improve the energy efficiency of the buildings and reduce the operating costs.

1.1. Building energy retrofitting

The energy retrofitting of buildings includes both passive and active solutions. The former is based, among other aspects, on improving the thermal quality of the envelope to reduce thermal losses and control solar gains. Conversely, dynamic solutions are aimed at optimizing the operating conditions of heating, cooling and air conditioning installations.

Both solutions can also be combined by, for instance, integrating renewable technology into the envelope, such as photovoltaic (PV) panels or solar collectors. In addition, systems such as heat pumps (HP) play a crucial role in energy transition, contributing to a decarbonized residential future as they can be fed with renewable energy sources, such as PV panels or wind turbines. The study conducted by Wang et al. [10], for example, demonstrates the ability of hybridization of technologies to electrify thermal demands and supply them with renewable sources.

1.2. Control of hybrid installations using storage

One of the main challenges of hybridizing renewable technology such as PV panels with HPs in buildings is to decouple energy generation instants from those of energy demand. After all, PV generation is higher when there is solar irradiation while energy demand is usually low at that time. This dynamism is further complicated when users influence buildings' energy consumption [11]. This mismatch results in inefficient use of energy sources, reducing the environmental and economic benefits of the hybrid system and increasing the energy exchanged with the national power grid, which leads to consequent issues in its management and stability. Therefore, to avoid the energy generation and demand dependence in buildings, two types of energy storage are usually used, and are in turn complementary: electrical energy storage (EES) and thermal energy storage (TES).

1.2.1. Combined control between EES and TES

To combine TES and EES systems, it is necessary to implement a control focused on optimizing energy, economic and/or environmental efficiency [12]. Possible approaches include: (1) prioritizing PV generation and self-consumption by storing surplus electricity; (2) prioritizing HP generation and storing thermal energy; (3) optimizing control to reduce economic costs; (4) maximizing renewable generation in periods of low carbon footprint for environmental optimization; and (5) focusing on the control strategy in a multi-objective optimization.

The benefits of combining TES and EES are discussed by Aneli et al. [13], where a building in Italy is analyzed with a self-consumption rate of 69.4% from a combined system, compared to 45.2% with TES and 60% with EES. Ren et al. [14] analyzed a system combining HP-PV, TES and EES incorporated in both residential and small public buildings, where mismatches between energy generation and demand, mitigated by time-of-use tariffs, are discussed. Multi-objective approaches are also implemented by Wang et al. [15] to maximize self-consumption and minimize costs when optimizing thermal and electrical storage systems. Similarly, Wang et al. [16] assessed the energy, economic and environmental performance of a hybrid HP, TES and EES systems for dwellings. Chen et al. [17] considered solar installation in public buildings with an emphasis on performance, lifecycle costs and CO_2 emissions. Ozcan et al. [18] studied hybrid systems for district heating and cooling, evaluating the impact of economic and meteorological factors.

1.3. Energy simulation as a compass for refurbishment

Energy simulations of buildings provide detailed models that account for energy demand and consumption of a building in a dynamic way, allowing comparison between different design and control alternatives to optimize energy use. Among the simulation programs, TRNSYS [19] stands out for its flexibility and modular integration, since it allows modeling the geometry and other physical parameters of the building, as well as thermal systems where advanced technologies and control strategies can be included.

Given the capability of the TRNSYS program, it is implemented in numerous research works where its potential is validated. In [20] the impact of climatic and operating conditions on the energy and economic performance of a solar photovoltaic air conditioning system with battery storage is simulated and evaluated. Ozcan et al. [21] developed a model to simulate a solar hybrid system, evaluating the impact of various photovoltaic and photothermal technologies based on the energy efficiency and exergy flows of the system, proposing an operational control strategy. Da et al. [22] simulated a PV-HP system with TES, validated by experiments. They analyzed annual operating characteristics, focusing on the energy conversion between TES, space heating (SH) and domestic hot water (DHW) demand. Yesilyurt et al. [23] combined TRNSYS and MATLAB to simulate a vanadium redox flow battery HP system, powered by solar PV and wind energy. Zeng et al. [24] simulated a solar system with hydrogen storage and fuel cell, compared to reference solar power systems with and without EES. Ołtarzewska et al. [25], evaluated the performance of a PV-HP system in a service building in six Polish cities by analyzing the impact of five system parameters on energy generation and consumption. The results detail how these factors affect the energy efficiency of the system. Rashad et al. [26] analyzed the annual energy performance of a three-zone building, evaluating heat transfer coefficients, heating and cooling demand, and the impact of thermal gains and losses.

1.4. Multi-objective optimization

Once the combined energy simulation of the building and its installation has been completed, multi-objective optimization can be applied to optimize system sizing and control. Multi-objective optimization is based on finding a set of solutions that show the most suitable trade-offs between several objectives, which are often in conflict. To find this set of ideal solutions, various techniques are used such as Multi-Objective Evolutionary Algorithms, including Non-dominated Sorting Genetic Algorithm II (NSGA-II) or Strength Pareto Evolutionary Algorithm II, Artificial Neural Networks using metamodels, or decomposition methods.

Literature shows many ways to optimize energy facilities in buildings. Zahra Benaddi et al. [27], merged TRNSYS and GENOPT to perform a multi-objective optimization analysis based on the Particle Swarn Optimization algorithm. They managed to reduce the life cycle cost, life cycle CO_2 and thermal discomfort hours by 14-18%, 20-26% and 11-21%, respectively, in a school located in Marrakech, Morocco. Furthermore, Gao et al. [28] and Wang et al. [29] combined TRNSYS with the JEPlus + EA software, employing the NSGA-II algorithm for multi-objective optimization to optimize the energy, economic and environmental performance of the studied buildings. Panagiotidou et al. [30] merged TRNSYS, DAKOTA [31] and Multi-Objective Genetic Algorithm to examine a multi-residential building located in Greece. They concluded that by implementing retrofit measures detailed in the research, such as increasing insulation, changing windows, including HPs and PV panels and so on, a maximum 87% and 96% reduction in GHG emissions and life cycle cost is achieved. Finally, Ghodrati et al. [32] examined the performance of an energy system including a HP, a flat-plate collector, Phase Change Material, TES and PV panels. They performed a multi-objective optimization using Engineering Equation Solver, TRNSYS and MATLAB software, and employ an algorithm called Multi Objective Particle Swarm Optimization.

1.5. Background

This work continues from the results obtained in several diagnostic studies and previous energy audits of 128 public rental buildings in the BAC [33]. These buildings were classified into 11 typological families that considered aspects such as energy rating, centralized or individual thermal installations and climate zone, as can be seen in Fig. 1 where a summary of building typologies of the analyzed stock is shown. The analysis demonstrated that 41% of buildings are not equipped with sufficient renewable installations, such as PV panels, although they had space for them. Therefore, the work in [33] proposed to incorporate aerothermal HP and PV systems, discarding geothermal, biomass and wind technologies.

A subsequent study [34] evaluated the potential for each public rental building to implement combined PV-HP technology, by means of specific indicators designed for the case study. This study resulted in the development of a matrix that prioritizes buildings for PV-HP integration interventions based on their technical feasibility. Despite the innovative results, the study admits limitations when calculating hourly heating and electricity demands since they were derived from simplified models based exclusively on the 11 representative buildings instead of each building. However, it is emphasized that the estimation of the incident solar radiation on each roof of the 128 buildings is performed with high accuracy on a case-by-case basis.

Besides, as the work of Hernandez et al. [35] pointed out, in the context of social housing, discrepancies are commonly observed between predicted and measured energy consumption, which influences decision making for energy renovation. These errors are directly reflected in the calculation of energy savings and compromise the credibility and feasibility of the proposed interventions.

1.6. Objectives

This study continues the previous research work [34], and overcomes the limitations including substantial innovative improvements as follows, see Fig. 2:

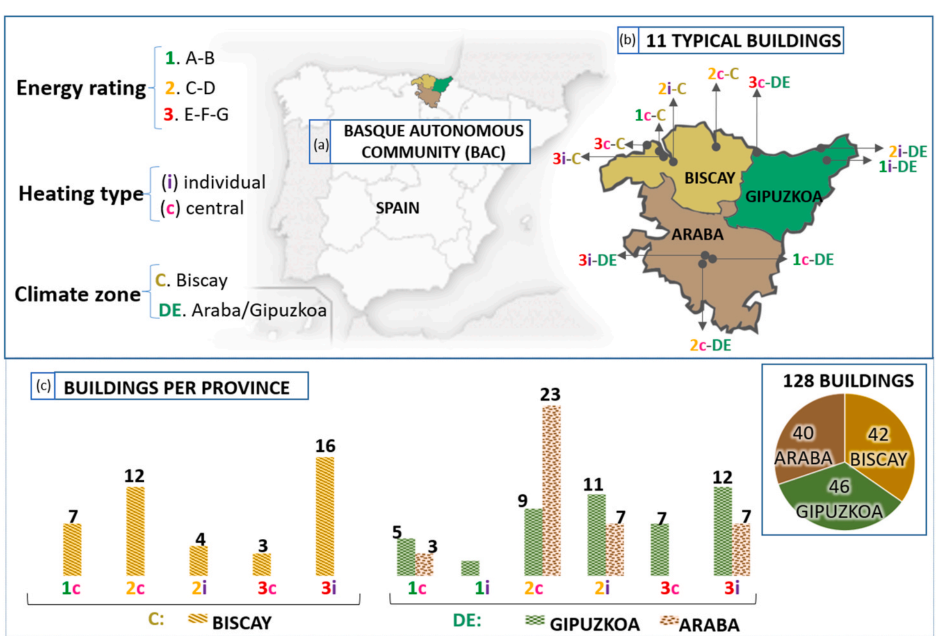

Fig. 1. Summary of the analyzed building stock. Adapted from [34].

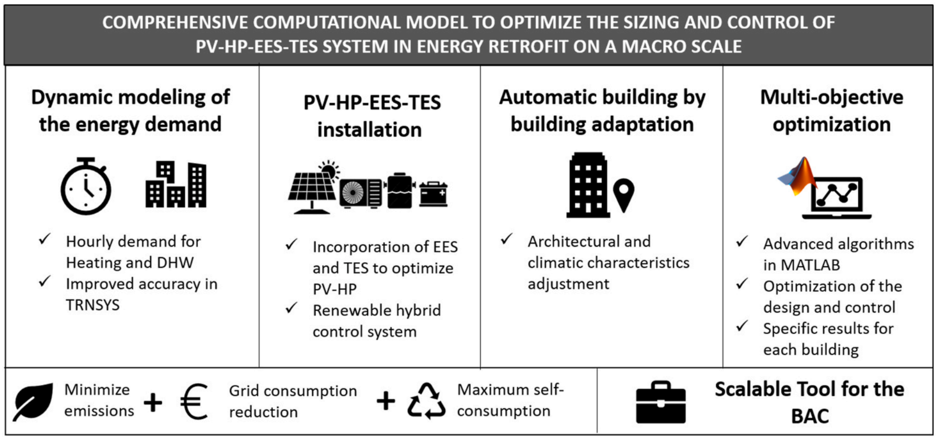

Fig. 2. Description of the proposed computational model.

- First, the uncertainty admitted on the calculation of the hourly SH demand is reduced. To do that, each building architectural and thermal characteristics are systematically defined in TRNSYS Trnbuild interface and simulated in Simulation Studio, where specific environmental conditions are included.
- Besides, each building is fully analyzed considering all thermal energy requirements, hourly DHW and SH demands.
- Regarding the installations, this work not only includes energy retrofitting using PV-HP, but also incorporates EES and TES storage systems.
- The last innovation deals with the optimization of the sizing of PV-HP-ESS-TES components as well as their control. This work makes a multi-objective optimization to maximize the use of renewable energy and minimize costs and pollutant emissions, following the process proposed by Prada et al. [36].

Thus, the present study develops a reference computational model in TRNSYS capable of systematically optimizing the sizing of PV-HP-EES-TES thermal installations and their control. This model is generic and applicable at a macro scale, while allowing adaptation to individual public buildings, thus bridging the gap in research corresponding to the lack of replicability and precision in terms of multi-objective optimization of the hybrid systems proposed as a guide for the energy rehabilitation of such buildings. On the one hand, the model considers the particular architectural characteristics and locations for each building and simulates the energy demand throughout the year. On the other hand, for the PV-HP-ESS-TES renewable installation, the multi-objective optimization results in the specific dimensions of the storage systems and the set-points for the control.

1.6.1. Novelties compared to current bibliography

Considering the literature review in the previous sections, it is observed that numerous studies analyze PV-HP hybrid systems combined with EES and TES, and integrated applications in the TRNSYS and MATLAB simulation environments ([10], [13], [14], [22]). However, these studies generally focus on individual buildings or small samples, with predetermined systems and defined control.

As shown in Table 1, among the studies analyzed, the general trends confirm that: (1) isolated cases are analyzed rather than large-scale contexts, (2) design and control are not addressed simultaneously, (3) the system is analyzed in a disaggregated manner, such as PV + HP or PV + storage, (4) trends are not analyzed to extrapolate the results to other contexts or to guide energy policies.

Given the circumstances, the contribution of this work lies in:

- The creation of an operational optimization framework that can be extrapolated and systematically adapted to the public housing stock.

Table 1
Focus of the reviewed works and contribution of this work.

LINES ADDRESSED	REFERENCES	LIMITATIONS	CONTRIBUTION OF THIS WORK
SYSTEM	Generally individual buildings with TRNSYS and MATLAB [10], [13], [14], [22]	Individual cases or specific typologies	Methodology scalable to the entire analyzed stock
CONTROL	Deterministic control strategies or heuristics [13], [15]	Control and design are optimized separately	Co-optimization of design and control variables
OPTIMIZATION	Isolated applications or in a few cases [27], [28], [29], [32]	Automation or systematic application for large-scale implementation is not considered	Automation adaptable to each particular case study
INTEGRATION	Disaggregated studies: PV + HP, PV + TES, PV + EES [14], [22], [25]	The optimized PV-HP-EES-TES set is not addressed	Simultaneous integration of technologies
SIMULATION	Isolated use of TRNSYS to evaluate strategies [20], [26]	An operational framework for making mass rehabilitation decisions is not created	Operational framework for planning the Public Energy Rehabilitation
ANALYSIS	Limited sensitivity and parametric detection analyses [15], [25]	No dominant variables or general trends identified	Identification of the S^{dw}_{usab} variable as key
SCALE	Limited to one or a few buildings [10], [17], [30]	Lack of methodologies extrapolatable to the urban scale	Framework that considers the design, control, automation, and scalability of the proposals

- Specific optimization for the particular building under study, allowing the optimal configuration to be obtained without the need for additional adjustments.
- Identification of the S^{dw}_{usab} variable as a dominant factor related to the optimal configuration of the system to be rehabilitated.
- Establishing a relationship between the PV availability of buildings and design and control strategies.

- Generating a framework for planning rehabilitation strategies at a macro scale and supporting energy policy decisions.

Therefore, the innovation of this study does not lie in analyzing hybrid systems, multi-objective optimization applications, or detailed simulations of individual buildings in isolation, as seen in the existing literature. Instead, this work introduces a novel integrated computational framework that combines detailed building-level dynamic simulation with multi-objective optimization in a fully automated and scalable workflow, which enables the selection of both optimal sizing and control parameters for the proposed system based on three main objectives: (1) reduction of CO_2 emissions, (2) reduction of grid energy consumption, and (3) maximization of PV self-consumption. The results offer optimal Pareto solutions that adapt to the specific energy needs of each building, making this model a key tool for increasing sustainability and energy efficiency on a macro scale within the framework of retrofitting the BAC's building stock.

2. Methodology

Multi-objective optimization integrates the dynamic behavior of the thermal installation and the building model together to supply the demands of each time step (5 min) throughout the year. Therefore, to combine the building model and the PV-HP-EES-TES installation, the models are fed with a set of data drawn from previous works [34] and [37]. Thus, after selecting the building to be optimized and linking the data automatically, the methodology is identical for all buildings, representing a hollistic approach at the macro scale.

Fig. 3 summarizes the main steps of the methodology consisting of (A) selecting and dynamically modeling the building and its demands; (B) connecting the generic PV-HP-EES-TES installation; and (C) obtaining the variables corresponding to the multi-objective optimization.

2.1. Building selection and demands

Thus, the previous step is based on downloading the following key elements obtained in previous works:

2.1.1. Building selection from a prioritized list

The buildings under study are selected from a prioritized list that ranks the 128 public rental buildings in the BAC from the building with the highest potential for integrating centralized PV-HP systems to the building with the lowest potential [34].

2.1.2. Estimation of DHW demands

The hourly DHW demand over a typical day is calculated according to the guidelines of DB-HB4 Annex F of the TBC [38] as follows (see Fig. 4):

$$D_i = D_p \cdot N_{peo.} \cdot N_{dw.} \cdot f_{cent.} \cdot \frac{P_i}{100} \tag{1}$$

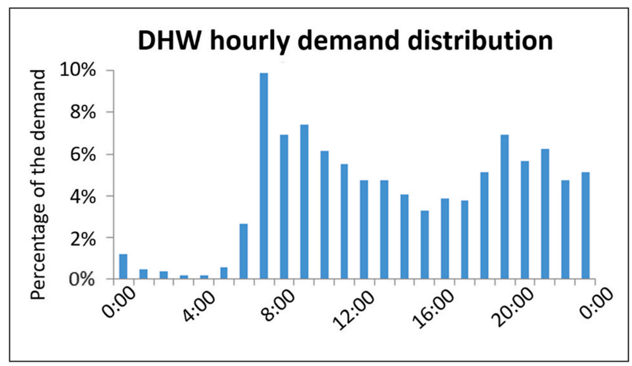

Fig. 4. Hourly DHW demand distribution in a typical day.

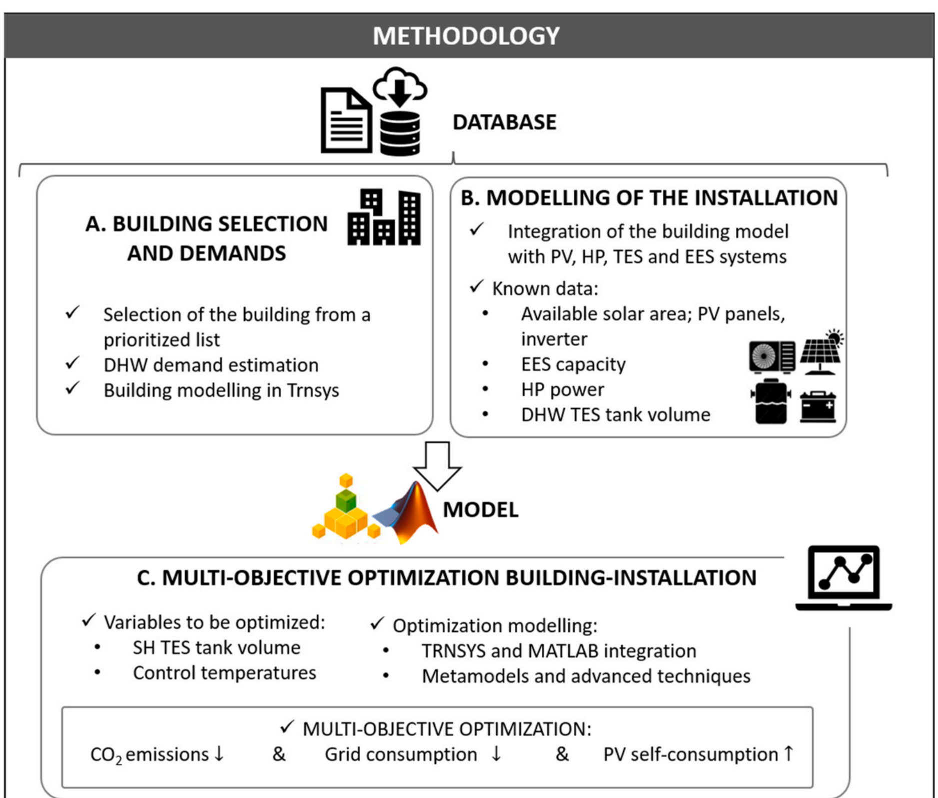

Fig. 3. Methodology proposed for the study.

Where:

- $i \in \{0, 1, 2, \ldots, 23\}$, is the hour of the day.
- D_i is the DHW demand at the i hour (litre).
- D_p is the daily DHW demand per person (litre/person·day).
- $N_{peo.}$ is the number of people per dwelling.
- $N_{dw.}$ is the number of dwellings per building.
- $f_{cent.}$ is the centralized factor.
- P_i is the percentage of the hourly profile at hour i, where $\sum_{i=0}^{23} P_i = 100$

2.1.3. Building modeling in TRNSYS and validation

The models of the buildings analyzed in this work are related to models validated in previous studies within the research framework of the public rental housing stock in the Basque Autonomous Community [35], [39]. As can also be seen in the ALOKABIDE publication [33], these models are based on empirical data such as:

- A large and statistically robust dataset related to energy consumption measured over three years in 481 dwellings.
- The consideration of model uncertainty based on the evaluation of the so-called Energy Performance Gap. This quantifies that measured consumption varies between 0.7 and 2.28 times with respect to the predicted value.
- The calibration of heating demand based on the actual monitored outdoor temperature and specific operating data recorded over several winters.
- Validation based on real consumption data and simplified calibrations for decision-making.
- On-site measurements and the definition of indicators for a multi-criteria evaluation as an auxiliary validation tool.

Using these data, the validation approach addressed in the cited works compares simulated energy consumption (and that obtained from energy performance certificates) with actual data measured in buildings, which yields the Energy Performance Gap. Therefore, it does not use a classic calibration approach such as the NMBE or the Cv(RMSE) proposed by ASHRAE (generally used for isolated cases and high-resolution calibrations). Instead, the model (1) considers the relationship between annual and projected energy consumption, (2) analyzes energy consumption by dwelling and by area, (3) compares actual consumption with theoretical consumption, and (4) quantifies the statistical dispersion due to the effects of user behavior.

This procedure is accepted for analyzing numerous dwellings and building complexes where user patterns produce significant variability. Furthermore, the objective of this modeling is related to modeling long-term trends rather than short-term accuracy. Thus, instead of achieving exact convergence between simulated and actual time values, it reproduces ranges, variabilities, and trends consistent with observed reality. It is, therefore, a model validated from the perspective of behavioral realism, not numerical precision.

The original models in this former works were developed using DesignBuilder and EnergyPlus software. However, the model's validity does not depend on the simulation platform but rather on (1) the physical description of the building (geometry, building envelope, energy system, etc.), (2) the specific usage conditions (weather conditions, usage patterns, etc.), and (3) calibration against monitored real-world data. Therefore, by transferring this information to the Trnsys interface using Type 56, the consistency of the already validated model is maintained and consistent with the observed trends.

Consequently, once the building has been selected, its geometry and orientation are obtained using Geographic Information Systems, and the relevant architectural parameters are derived from the available data [34]. As s said, the thermal behavior throughout the year is simulated in TRNSYS, combining the Trnbuild and Simulation Studio interfaces.

2.2. Model of the installation

As mentioned, the adjusted model of the building under study is combined with the new PV-HP-EES-TES system to be designed, where multi-optimization algorithms are implemented, and the necessary parameters and variables are calculated.

2.2.1. Building model integration into the PV-HP-EES-TES system and validation

It should be noted that there are multiple configurations for designing a hybrid installation that combines PV and HP and one of the main challenges is the proper positioning and integration of TES inertia tanks. In the context of this study, which aims to systematically retrofit installations with renewable technology, the premise is the existence of a typically centralized installation that uses a natural gas boiler to supply both SH and DHW through an inertia tank (TES_{DWH}). Consequently, the adopted approach for retrofitting is to modify as little as possible the configuration of the existing equipment, so that the new components, HP, PV, TES_{heat}, and EES, are incorporated as additional elements without substantially altering the original infrastructure. Thus, the gas boiler and TES_{DHW}, included as part of the base installation, are maintained as auxiliary devices to meet DHW demand peaks, ensuring service continuity without significantly modifying the previous operational structure. Fig. 5 shows the layout of the main components of the installation, according to the previous setup.

This installation is defined in TRNSYS, where the objective is to determine the key parameters of the inertia components and their control, adapted to the characteristics of each building. Table 2 shows the Types used for system configuration in TRNSYS.

In this regard, the priority is to directly power the HP with the energy generated by the PV panels, which operate in conjunction with the thermal storage TES_{heat} and TES_{DHW}, while the excess electrical energy is stored in EES batteries, which discharge when there is no PV generation but there is consumption in the HP. Thus, the heat stored in the TES systems decouples the demand from the energy generation, allowing the system to meet the demand peaks for both DHW and SH, which helps to avoid short cycles of the HP.

The validation of the proposed hybrid system for energy retrofitting is guaranteed at both the component and complete system levels. Regarding the specific components, the installation uses the standard types and TESS components from the TRNSYS library shown in Table 2. As verified in the TRNSYS mathematical manual, all these components are based on consistent formulations of physical, mechanical, and thermodynamic phenomena, created and validated within the TRNSYS environment. Furthermore, they have been experimentally validated and have been frequently used to model systems in recent literature. Specifically.

- Photovoltaic panels have been validated using real energy generation data. Kanyaurusoke et al. [40] demonstrate consistency between simulation in TRNSYS and experimental values with regression coefficients of $R^2 \approx 0.78$.
- The photovoltaic system combined with the battery and inverter in TRNSYS was experimentally validated by Barrena et al. [41] achieving relative errors of less than 10% with respect to the energy generated and stored, thus ensuring the reliability of the components.
- The heat pump type of TRNSYS considers the experimentally validated performance curves introduced. Similarly, authors such as Kassai [42] and Ethirveerasingham et al. [43] validated these models with real-world consumption data and experimental COP measurements, confirming their consistency with actual operating values.
- Inertial thermal storage systems of TRNSYS are validated, for example, in the work of Roumpedajus et al. [44] and Haddouche et al. [45], which demonstrates that internal temperature

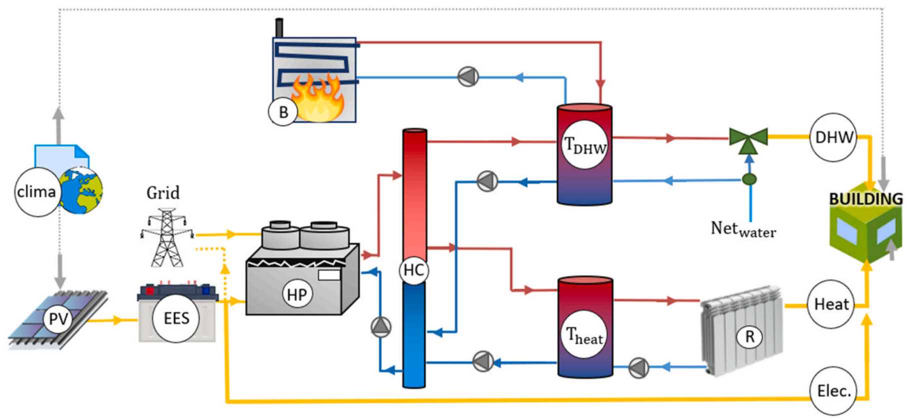

Fig. 5. Model of the hybrid PV-HP-EES-TES installation.

Table 2
TRNSYS component Types used for the system configuration.

COMPONENT	*TYPE*	*DESCRIPTION*
PV PANEL	*562*	*Simple Glazed or Unglazed PV Panel*
HEAT-PUMP	*525*	*Variable Speed Compressor Air (Source) -to-Water Heat Pump*
BATTERY	*549*	*Lithium-ion Battery*
INVERTER	*48*	*Peak-power tracking collector, battery, monitoring of state of charge.*
STORAGE TANK	*1534*	*Vertical Cylindrical Storage Tank with Immersed Heat Exchanger*
BOILER	*122*	*Boiler*
RADIATOR	*526*	*Heat Emitter/Simple Radiator*
BUILDING	*56*	*Multizone Building*

stratification and transient trends deviate by approximately 5% from experimental values.

- Carlon et al. [46] validate boiler TRNSYS models under various conditions, both steady-state and dynamic, and calculate deviations of less than 10% in resource consumption.
- Other studies, such as those by Draou & Ahmadi [47] and Gök et al. [48], experimentally validate other systems using components in TRNSYS and conclude that they reliably represent temperature profiles, COPs, and energy consumption trends under real-world conditions.

Thus, it can be concluded that the components used in this work are individually validated and widely used in the literature. Combining these models with previously validated building models ensures that the overall system behavior is accurate and consistent with real-world trends.

Regarding the reliability of the overall representation of the proposed hybrid system, consistent behaviors and trends are observed, such as: heat pump COPs within typical recorded ranges, photovoltaic generation that agrees with previously performed QGIS analyses, increased self-consumption when inertial components are integrated, etc. It is important to emphasize that the proposed PV-HP-EES-TES system is not based on a static configuration but is generic and adaptable to each specific building. Therefore, the component capacities, main characteristics, and control variables are determined after implementing the multi-objective optimization code in each case. Consequently, this work analyzes a wide range of solutions and configurations, not a predefined system. This fact makes it almost impossible to experimentally validate each solution and, therefore, the validation of the system is accepted based on the physical consistency of the results consistent with the literature.

2.2.2. Data extracted from databases

To reduce the variables in the optimization process, the following relationships obtained from previous databases are assumed:

- The useable solar area data previously calculated for each roof, obtained thanks to the methodology followed [34], is considered, and thus the number of PV panels (Type 562) and the capacity of the inverter (Type 48) to be installed in each case are known (Eq. (2)). These data allow sizing the EES battery (Type 549) by defining its cells in series and number of strings in parallel (dependent on the system's power consumption).

The capacity of the inverter is calculated as follows:

$$P_{inv.} = \left(\frac{S_{usab}}{S_{panel}}\right) \cdot P^{PP}_{panel} \cdot f_{sec.} \tag{2}$$

Where:

- o S_{usab} is the useable solar area obtained in the previous work [34].
- o S_{panel} is the surface of the PV panel, which has a value of 1,63 m^2.
- o P^{PP}_{panel} is the Peak Power of the PV panel, 270 W.
- o $f_{sec.}$ is the value of the security factor, which is 15%.

- The maximum power required by the HP (Type 525) is calculated based on the instantaneous results of the combined SH and DHW demand for each building, obtained from the databases [34] related to the previous individual thermal model.
- Existing radiators in the building are retained, as they operate efficiently over a wide range of temperatures. The heat transfer surface area of the radiators (Type 526) is determined based on the specific characteristics of each building.
- The TES_{DHW} tank volume is also known for each building. If the specific value is not on the data set, this value is determined by the Technical Guide on Centralized DHW published by IDAE [49], that proposes an accumulated volume of around half of the total daily DHW demand. As shown before, this value depends on the number of buildings and the factor of centralization. With a conservative perspective, this work considers accumulating the 60% of the total daily DHW demand as follows:

$$V^{DHW}_{TES} = \dot{m}_{total} \cdot 0.6 \tag{3}$$

2.3. Multi-objective optimization of the building-installation model

Therefore, the main parameters of the PV and HP systems are integrated from the beginning of the multi-optimization process based on the specific building under study, and the main challenge relies on the sizing of the thermal storage systems and their control, for which the electric self-consumption is prioritized.

2.3.1. Variables to be optimized

The variables included in the optimization process are selected to ensure compliance with current regulations and to enable effective control strategies:

- The Spanish Technical Building Code [5] requires maintaining the water inside DHW tanks at a temperature above 60°C, to prevent the proliferation of legionella. Therefore, the TES_{DHW} tank must operate at a temperature close to this value and is optimized for each case considering temperatures between 58°C and 69°C. To ensure this range, the tank is preheated with the heat supplied by the HP and is then heated with the auxiliary contribution of the boiler. As mentioned, the volume of the TES_{DHW} tank is predefined [49].
- The temperature inside the TES_{heat} tank is also maintained within a specific temperature range, set within the limits that guarantee the operational efficiency of the heat pump (between 30 and 70 °C). The exact value of this range is set after running the multi-optimization process to find the optimal values for each specific building, as is done with the value of its volume.

Considering all this, the variables to be optimized are:

- Design variables: The volume of the TES_{heat} tank for SH, V_{TES}^{heat}.
- Control variables: The temperature thresholds that govern the thermal control of the system, which are the temperatures of the TES_{heat} and TES_{DHW} tanks, from which the control intervenes:
- o For the SH supplier TES_{heat} tank, the primary heating circuit pump activates when the internal temperature of the TES_{heat} falls below the lower threshold T_{heat}^{low}; and it remains on until T_{heat}^{high} is reached.
- o Similarly, for the DHW supplier TES_{DHW} tank, the primary circuit pump starts when the internal temperature falls below the T_{DHW}^{low} threshold and remains on until the T_{DHW}^{high} value is reached.
- o As mentioned, under conditions of high thermal demand, the boiler acts as an auxiliary system to ensure the availability of energy and the safety of the DHW. Therefore, the pump associated with the boiler activates when the temperature in the TES_{DHW} tank exceeds the T_{Bo}^{low} threshold, and continues operating until $T_{Bo}^{high}$is reached.

Therefore and in order to reduce the computational load associated with the simulation process, the upper and lower limits of the admissible ranges for each optimization variable are defined in advance, as well as the corresponding discretization step, see Table 3.

2.3.2. Optimization model

The combined building-installation system is optimized to achieve three main goals: (1) reduce CO_2 emissions, (2) decrease dependence on grid electricity, and (3) maximize the self-consumption of energy generated by PV panels. These objectives were intentionally chosen and are related to the main purpose of defining optimal energy and environmental design and control strategies for the rehabilitation of the public rental housing stock. In this context, economic criteria are not as high a priority in the optimization problem, but they were implemented in a subsequent analysis. The yearly value of the energy imported from the grid is obtained as a cumulative output of the Inverter type-48 in TRNSYS and the other two indicators are calculated as follows:

- Yearly CO_2 emissions indicator:

$$kgCO_2 = \sum_{t}^{8760} \left(E_{FromGrid}^{t} \cdot f_{elec.} + Q_{boil}^{t} \cdot f_{NG} \right) \tag{4}$$

Where:

- o $E_{FromGrid}^{t}$ is the energy imported from the electricity grid at each time-step (kWh).
- o Q_{boil}^{t} is the energy consumption of the boiler at each time-step (kWh).
- o $f_{elec.}$ is the CO_2 emission factor of the electricity ($kgCO_2$/kWh) [50].
- o f_{NG} is the CO_2 emission factor of the natural gas ($kgCO_2$/kWh) [51].
- Yearly PV self-consumption increasing indicator:

$$E_{PVtoLoad} = \sum_{t}^{8760} \left(E_{ToLoad}^{t} - E_{FromGrid}^{t} \right) \tag{5}$$

Where:

- o E_{ToLoad}^{t} is the energy derived to the HP electricity load at each time-step (kWh).

Therefore, after identifying the main characteristics of the equipment and operating conditions, the key parameters to optimize are set (the V_{TES}^{heat} volume of the TES_{heat} and the temperature thresholds of TES_{heat} and TES_{DHW} that trigger the control). The optimization is carried out combining the dynamic simulation in TRNSYS with the algorithmic optimization in MATLAB, and provides several possible technical solutions in a Pareto front to ensure the most efficient and functional design of the PV-HP-EES-TES installation.

The algorithm itself is developed by Prada et al. [36], which is based on generation-based control approach. Its performance has been validated in various scenarios, demonstrating the ability to obtain competitive solutions with a reduced number of simulations even in high-dimensional problems.

Metamodels are used to reduce the computational load of the optimization, and a Multi-Adaptive Regression Spline method is employed. The optimization algorithm samples the initial population uniformly across the search space using the Latin Hypercube Sampling technique. Once the initial configurations have been simulated, the fitness functions are evaluated, which are the annual (1) CO_2 emissions, (2) electricity drawn from the grid and (3) PV self-consumption. The code subsequently fits the meta-model and employs it to filter out unpromising solutions, allowing the simulation in TRNSYS to be performed only for the promising ones. Each simulation is performed with a time step of 5 min over the 8760 annual hours.

Once the Pareto frontier is created, the Weighted Sum Method (WSM) is used to select the optimal set of variables for each case. This method assigns a weight to each of the objectives and, after normalizing each objective indicator, calculates the weighted sum of the normalized values for all candidate optimal points obtained from the multi-objective optimization. As it is known, the optimal alternative is the one with the lowest aggregate value. In this specific methodology, 30%, 20%, and 50% weight values were assigned to the objectives of (1) minimizing CO_2 emissions, (2) minimizing the dependence on grid electricity and (3) maximizing PV self-consumption, respectively.

Table 3
Interval and step size of the variables to be optimized.

PARAMETER	*UNIT*	*RANGE*	*STEP*
V_{TES}^{heat}	m^3	[6-10]	1
T_{heat}^{low}	$^\circ C$	[30-55]	5
T_{heat}^{high}	$^\circ C$	[45-70]	5
T_{DHW}^{low}	$^\circ C$	[58-61]	0.5
T_{DHW}^{high}	$^\circ C$	[61-69]	1
T_{Bo}^{low}	$^\circ C$	[60-64]	0.5
T_{Bo}^{high}	$^\circ C$	[62-69]	0.5

3. Case study

As mentioned above, the work involves analyzing the BAC's public rental housing stock. This consists of 128 buildings (7614 dwellings), previously characterized and classified into 11 typological families according to their energy, climate and construction characteristics.

Furthermore, considering the previously published priority ranking [34], which showed the technical feasibility of renovating the buildings through PV-HP hybridization, 6 of the 11 typologies suitable for this solution have been selected. The remaining typologies have been ruled out, due to technical or geometric limitations, and require alternative energy renovation solutions.

3.1. Specific characteristics of the six buildings under study

Thus, this work presents the results of the refurbishment proposals for the following six representative buildings, selected as typical examples of each candidate typology.

- Typology 3c-C (3 buildings): building coded as (03)3c-C.
- Typology 2c-C (12 buildings): building coded as (04)2c-C.
- Typology 1c-C (7 buildings): building coded as (03)1c-C.
- Typology 1c-DE (8 buildings): building coded as (01)1c-DE.
- Typology 3i-C (16 buildings): building coded as (02)3i-C.
- Typology 1i-DE (2 buildings): building coded as (02)1i-DE.

For ease of understanding and due to the length limitations of this article, only the results for these six buildings are shown (see specific characteristics in Table 4). However, each can be considered representative of its respective typological family and, therefore, the results are characteristic of a total of 48 buildings (2344 dwellings), representing approximately 40% of the public housing stock analyzed. Consequently, even if each renovation strategy must be designed individually for each specific building, the results presented here allow extrapolating robust conclusions on an aggregate scale and facilitate the evaluation of the potential of macro-scale energy renovation strategies.

These buildings analyzed present a wide range of:

- Occupancy densities “dw”: between 11 and 171 dwelling per building.
- Available roof area “S_{usab}”: between 277 and 1134 m^2, which is decisive for integrating PV panels.
- Maximum heating power “$\dot{Q}_{heat}^{Max}$”: from 15.6 to 213 kW.

So that the analysis covers heterogeneous constructive and energy conditions of various buildings types. The key normalized variable for interpreting the results is “S_{usab}/dw”, as it relates to the PV generation capacity per dwelling and, therefore, to the degree of green electrification required to power PV-HP systems with storage.

To explain the specific implementation of the methodology, the building coded as “(04)2c-C” is deeply explained and the corresponding results of the rest of the buildings are afterwards given.

3.2. Detailed application of the specific building "(04)2c-C"

The building “(04)2c-C” is located in a climate zone “C”, currently contains a centralized installation based on a boiler “c”, and has an energy rating label of “C”. As mentioned, the useable floor area is 662 m^2 and consists of a ground floor and 4 conditioned upper floors with 30 public rental apartments, with an estimated DHW demand of 2140 L/day, see Fig. 6.

3.2.1. Modelling of the rehabilitation system of “(04)2c-C” building

The building's energy model, developed by integrating Trnbuild and Simulation Studio in TRNSYS, is coupled with the generic configuration of the hybrid PV-HP-EES-TES installation (see Fig. 5). The thermal demand for SH, which ensures comfort conditions, is calculated at each time step of the simulation and optimization process, which is adjusted all the time to the operational conditions of the renewable hybrid system and external climatic variables. The values of the pre-established parameters for the “(04)2c-C” building, obtained from the databases, are:

- Useable solar collection area: 367 m^2.
- Number of PV panels and inverter: 225 PV modules and an inverter capacity of 70 kW.
- Electric energy storage EES parameters: 14 cells in series, 6 in parallel and 100 Ah cell charge capacity.
- Maximum HP power: 50 kW.
- Total radiator surface area: 300 m^2.
- Volume of the DHW TES tank (V_{TES}^{DHW}): 1285 L.

4. Results

This section presents the results of the optimization of building "(04)2c-C", followed by the analogous values for the other representative buildings analyzed.

4.1. Specific individual results of the “(04)2c-C” demonstrator building

4.1.1. Multi-objective optimization of the “(04)2c-C” building-installation model

Once all the information from the databases has been updated, the integrated computational model is executed to optimize the sizing and control strategies of the hybrid PV-HP-EES-TES system, for a future energy retrofit approach of the selected building.

The optimization process generates a dataset with all the simulated combinations of the system parameters to be optimized (V_{TES}^{heat} and the temperatures influencing the control), including also the yearly values of the indicators: (1) CO_2 emissions (kgCO_2), (2) energy imported from the grid (kWh), and (3) PV self-consumption (kWh). Thus, the two-dimensional representation of these (Fig. 7(a–c)) results allows analyzing the interaction between two of the objectives, where it is verified that:

- As shown in Fig. 7 (a), the relationship between reducing grid consumption “$E_{FromGrid}$” and maximizing photovoltaic self-consumption “$E_{PVtoLoad}$” is strong and can be approximated to a linear function, implying that there is a proportional relationship between achieving both objectives. That is, when one of the objectives decreases, the other also decreases proportionally. This suggests that one of the objectives to be optimized can be modified, such as by including cost minimization objectives.
- In contrast, the maximization of PV self-consumption and the reduction of CO_2 emissions shows a weaker dependency, resulting in a smaller number of non-dominated solutions, see Fig. 7 (b), and a more open representation of the front, also influenced by the scale differences between the objectives, see Fig. 7 (c).

For greater clarity and given the triple objective of the computational model, the results are represented in a three-dimensional space to identify the solutions. Fig. 7 (d) represents the global Pareto front with the optimal solutions (orange points) and excludes the non-optimal solutions (blue points). Therefore, it is a three-dimensional Pareto front with shows nonlinear trade-offs between objectives. This Pareto point clouds justify the functional non-dependence of the objectives and indicate that some have conflicting criteria.

Consequently, the point on the Pareto front that offers the least Euclidean distance from the three objectives is chosen (black point in Fig. 7(a–d)) prioritizing the maximization of the PV self-consumption. Table 5 contains the specific values of the design and control variables obtained from the multi-objective optimization process for the “(04)2c-C” building.

Table 4
Construction characteristics of the analyzed buildings.

					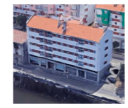	
Building code	*(01)3c-C*	*(04)2c-C*	*(03)1c-C*	*(01)1c-DE*	*(02)3i-C*	*(02)1i-DE*
Climate zone	*C*	*C*	*C*	*DE*	*C*	*DE*
Construction year	*2007*	*2009*	*2010*	*2014*	*2006*	*2016*
dw: dwelling number	*40*	*30*	*39*	*171*	*11*	*20*
S_{roof} (m^2)	*900*	*662*	*583*	*1935*	*636*	*990*
S_{usab} (m^2)	*577*	*367*	*277*	*1134*	*330*	*856*
$\dot{Q}_{heat}^{Max}$ (kW)	*100.5*	*33.5*	*47*	*213*	*40.3*	*15.6*

Fig. 6. Selected building photo.

4.1.2. TRNSYS simulation results of the "(04)2c-C" building

Once the parameters of V_{TES}^{heat} are determined and the control thresholds are established, they are incorporated as parameters into the global model on TRNSYS, which is then simulated with a time step of 0.125 h throughout the year. As an example of the results and for space reasons, the following graphs represent the period between February 12 and 20 (from 1006 h to 1224 h).

- Fig. 8 (a) shows the evolution of PV production, HP electricity consumption, energy purchased from the grid, and self-consumption from the interaction with the EES system, where positive values indicate charging and negative values indicate discharging of the battery.
- Fig. 8 (b) shows the operation of the SH thermal tank (TES_{heat}). As shown, the heating control is based on the activation of the primary heating circuit pump when the TES_{heat} temperature drops below T_{heat}^{low} (55 °C) and deactivates upon reaching T_{heat}^{high} (70 °C). In turn, the secondary circuit is connected to the building's radiators, whose activation depends on the building's indoor comfort temperature.
- Regarding the TES_{DHW} tank of Fig. 8 (c), this is charged through two circuits: the main one associated with the HP and the auxiliary one with the boiler (see Fig. 5). According to the optimized control, the lower temperature threshold of the tank T_{Bo}^{low}, below which the boiler activates until the tank temperature increases to T_{Bo}^{high} (62.5 °C), when the boiler deactivates and the HP continues to supply heat, operating until it reaches the upper limit of T_{DHW}^{high} (69 °C), at which temperature the thermal supply is interrupted.

As overall results of the indicators, the combined building-installation model presents (1) CO_2 emissions of 3130 kg, (2) an energy demand imported from the grid of 2380 kWh, and (3) PV self-consumption of 4555 kWh annually, representing a point inside the Pareto frontier with the minimum emissions, minimum grid consumption and maximum self-consumption values achievable specific to the building under study.

4.2. Overall results for the analyzed buildings

Similarly, the rest of the buildings selected are analyzed to design and control the PV-HP-EES-TES hybrid systems as a renovation proposal. Thus, multi-objective optimization is applied and three-dimensional Pareto fronts associated with the three objectives are generated. The specific solution for each case is selected, and shown as a black dot in Fig. 9, by giving greater relative weight to the objective of maximizing photovoltaic self-consumption.

4.2.1. Multi-objective optimization specific results of all the buildings

Table 6 shows the specific results of the optimal design and control values which, although they correspond to typologically heterogeneous buildings, converge in the following trends:

- Value of V_{TES}^{heat}:

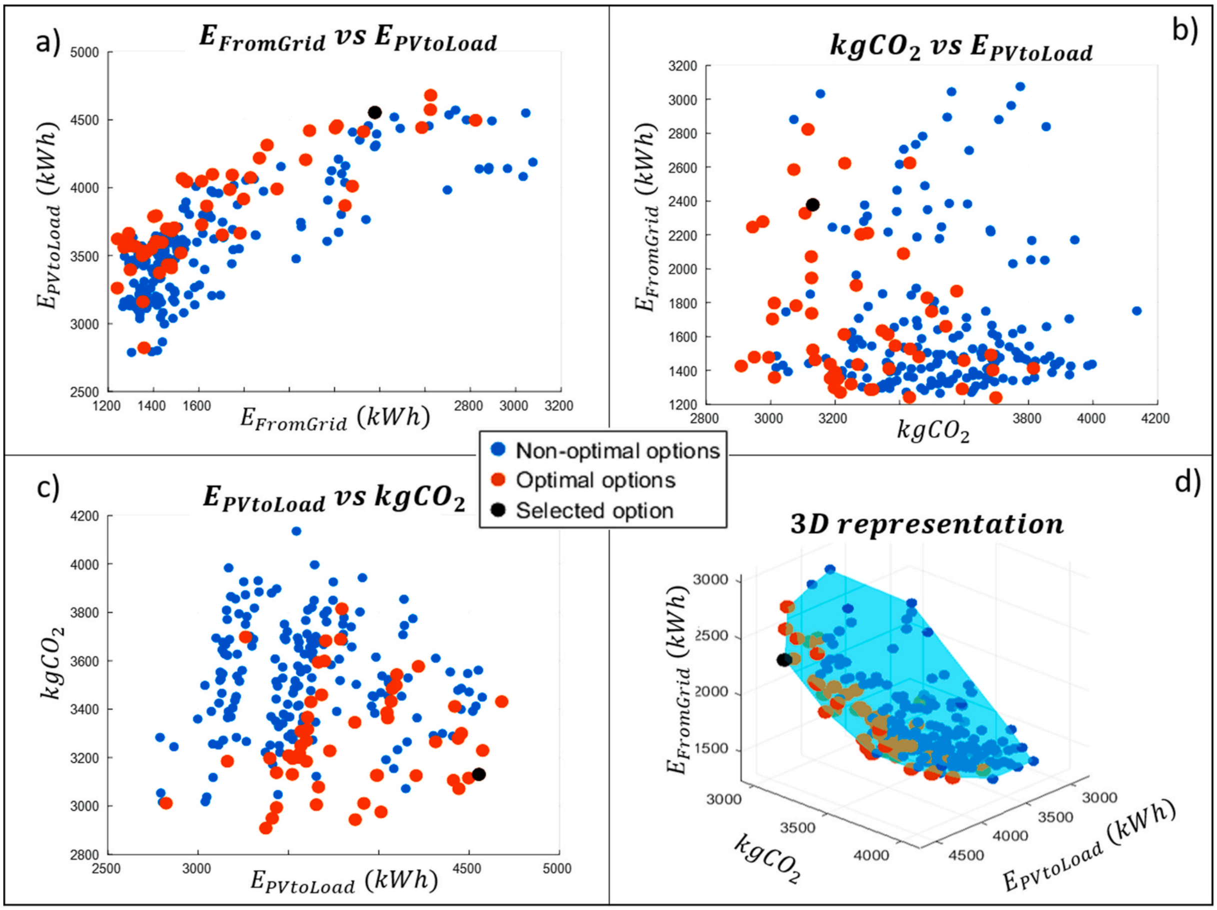

Fig. 7. Solutions found after conducting the multi-objective analysis with MATLAB.

Table 5
Selected optimized parameters for the installation model.

V_{TES}^{heat}	T_{heat}^{low}	T_{heat}^{high}	T_{DHW}^{low}	T_{DHW}^{high}	T_{Bo}^{low}	T_{Bo}^{high}
$7\ m^3$	$55\ ^\circ C$	$70\ ^\circ C$	$58\ ^\circ C$	$69\ ^\circ C$	$62\ ^\circ C$	$62.5\ ^\circ C$

- o In all cases analyzed, the optimal volume of the heating tank is between 6 m^3 and 9 m^3, covering almost the full range set. A detailed analysis shows that the relationship between storage volume per dwelling (V_{TES}^{heat}/dw) and useable rooftop space per dwelling (S_{usab}/dw) shows an approximately linear trend, see Fig. 10.

Therefore, it can be concluded that the value of this volume is not only determined by the total demand of the building (linked to the number of dwellings), but rather by the S_{usab}/dw ratio, which determines the amount of PV production available for each dwelling.

- o The three buildings with the lowest number of dwellings have a volume of 6 m^3, corresponding to the lower limit of the imposed range. This suggests that this lower limit could be reduced for future analysis and to explore a wider range of solutions.
- o In general, it can be interpreted that the optimal volume of the heating TES depends on the PV generation potential and the electricity consumption of the heat pump.
- • Set points for heating circuit control, T_{heat}^{low} and T_{heat}^{high}:
- o The activation and deactivation temperatures of the heating tank have greater variability. Buildings with lower PV potential per dwelling (S_{usab}/dw) are assigned lower temperature thresholds (T_{heat}^{low} = 30 °C), which suggests that priority is given to the pump operating at low temperatures and higher COP.
- o Buildings with higher S_{usab}/dw values are associated with higher thresholds (55-70 °C), encouraging greater thermal storage from PV surpluses.
- o In general terms, it is estimated that the optimal control strategy is directly related to S_{usab}/dw capacity and does not depend so closely on the size of the building.
- • Set point for DHW circuit control, T_{DHW}^{low} and T_{DHW}^{high}:
- o The thresholds in all buildings have similar tendencies. The upper limit is always the imposed value of 69 °C, which is related to health measures. Increasing the range in subsequent analyses does not seem advisable, as increasing the storage temperature would only increase storage losses and subsequent mixing with cold mains water to supply the DHW.
- o The lower limit values range from 58 to 64 °C, depending on the type of heat pump operation (high or low temperature) and the relationship with the auxiliary boiler.

4.2.2. Normalization by S_{usab}^{dw} indicator of specific results for extended interpretation

Although optimization results depend on numerous energy, operational, structural and other variables, preliminary analysis has shown that the PV potential value per dwelling "$S_{usab}^{dw} = S_{usab}/dw$" is key to identifying trends that can be extrapolated to the entire housing stock analyzed. This parameter includes the useable roof area and the number of dwellings in each case. After all, the gross variable of the number of dwellings serves as an aggregation factor, but does not allow for interpretation of the energy performance results. Therefore, the overall

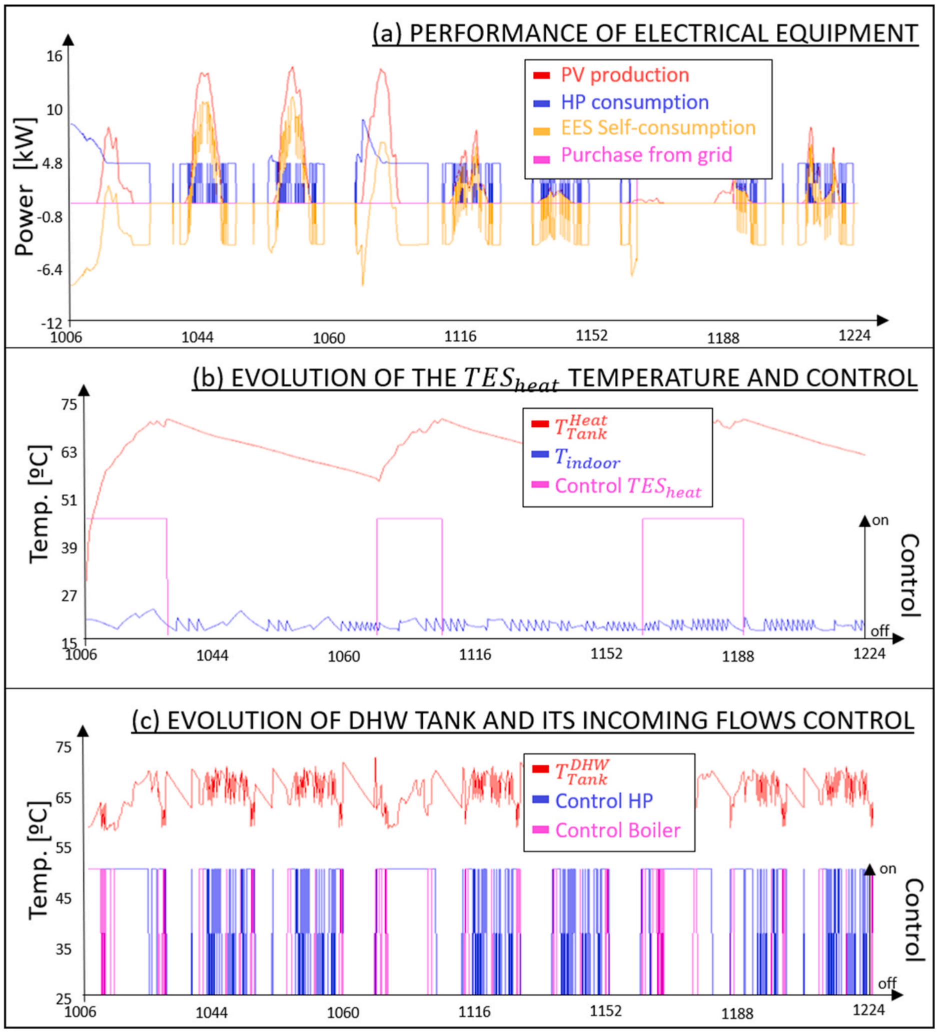

Fig. 8. Evolution during February of (a) the performance of the electrical equipment (b) the TES_{heat} temperature and control, and building indoor temperature (c) DHW tank and its incoming flows control.

results of the optimization (1) minimum CO_2 emissions in kg, (2) minimum grid energy consumption, and (3) maximum PV self-consumption over the year, have been normalized based on the value of S_{usab}^{dw}, see Table 7.

According to the normalized results, there is a correlation between the PV potential per dwelling "S_{usab}^{dw}" and the optimized values of (1) minimum annual emissions of kg CO_2 (Fig. 11 (a)) and (2) minimum grid electricity consumption (Fig. 11 (b)). It can be seen that the larger the S_{usab}^{dw}, the more significantly both values are reduced. Although the number of buildings analyzed is limited, the normalization variable does not depend on the specific type of building and, therefore, this relationship can be approximated to a decreasing potential function, shown in Fig. 11.

In any case, it is important to distinguish between the statistical correlation provided and the functional dependence between the objectives. In the regression analysis of Fig. 11, it can be observed that both CO_2 emissions and normalized grid consumption have similar trends when plotted against S_{usab}^{dw}, with an $R^2 \approx 0.6$. However, these relationships are neither linear nor deterministic. It can be assumed that these objectives may depend on factors such as photovoltaic availability S_{usab}^{dw}, but they remain independent in the optimization space.

Furthermore, it is shown that the third objective of (3) photovoltaic self-consumption, even when normalized with respect to S_{usab}^{dw}, does not show any clear correlation. This may be due to its dependence on different operational strategies, the management of inertial equipment, and the adaptive control itself. Therefore, this objective is related to independent information.

From a physical and strategic perspective, the objectives address three complementary factors oriented toward public policy: (1) minimizing CO_2 emissions is related to environmental impact; (2) minimizing grid consumption is related to energy independence; and (3) maximizing photovoltaic self-consumption is related to local renewable integration and system efficiency.

Including economic indicators would address important issues, but this would require redefining the problem, which increases computational cost considering the scale of analysis. Therefore, the economic evaluation was analyzed a posteriori without modifying the optimization algorithm.

4.2.3. *Identification of clusters for extrapolation to macro-scale*

Based on the results, two regimes related to the variable S_{usab}^{dw} can be identified. The third group considers intermediate situations.

- Cluster A: buildings with high S_{usab}^{dw} value (>25 m^2/dw)
  - o Includes buildings with large PV available roof areas, probably with low housing density.
  - o If they are refurbished using PV-HP-TES-ESS strategies with optimized design and control variables, these buildings will be

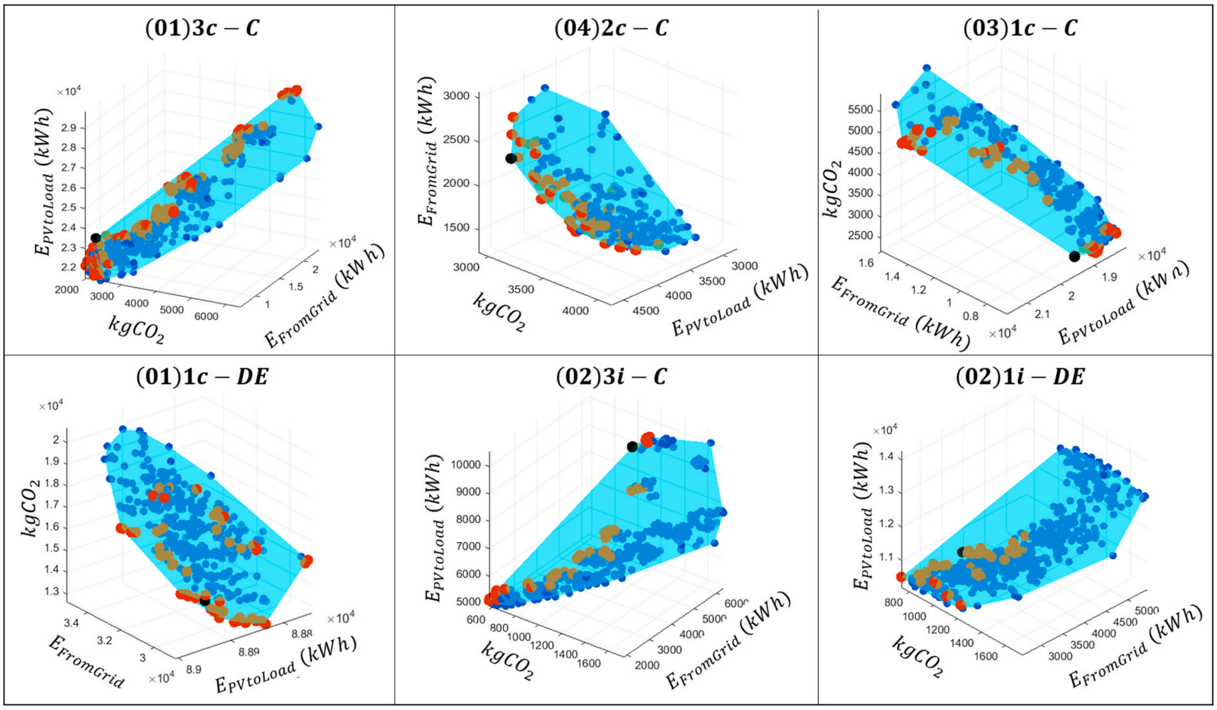

Fig. 9. Multi-objective optimization results of the analyzed buildings.

Table 6
Specific results of the optimal design and control values of each building.

Building	*dw*	S_{usab}	V_{TES}^{heat}	T_{heat}^{low}	T_{heat}^{high}	T_{DHW}^{low}	T_{DHW}^{high}	T_{Bo}^{low}	T_{Bo}^{high}
(01)3c-C	40	577m^2	6 m^3	30 °C	45 °C	61 °C	69 °C	63 °C	66 °C
(04)2c-C	30	367 m^2	7 m^3	55 °C	70 °C	58 °C	69 °C	62 °C	62.5 °C
(03)1c-C	39	277 m^2	6 m^3	30 °C	45 °C	61 °C	69 °C	63 °C	62.5 °C
(01)1c-DE	171	1134 m^2	7 m^3	30 °C	45 °C	59 °C	69 °C	62 °C	62.5 °C
(02)3i-C	11	330m^2	9 m^3	55 °C	70 °C	59 °C	69 °C	62 °C	62.5 °C
(02)1i-DE	20	856m^2	6 m^3	40 °C	55 °C	60 °C	69 °C	64 °C	64.5 °C

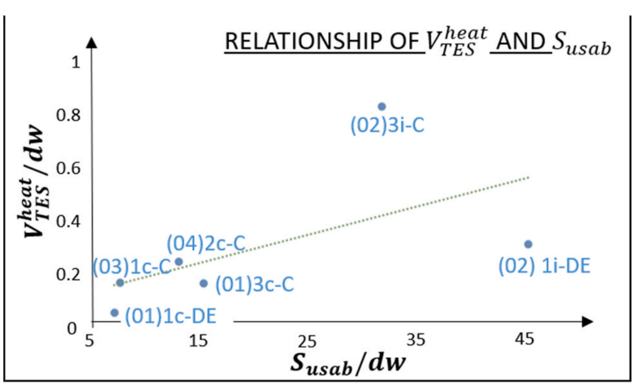

Fig. 10. Relationship between V_{TES}^{heat}/dw and S_{usab}/dw.

characterized by (1) low CO_2 emissions, (2) low grid dependency and (3) high PV self-consumption.

o The control strategy is linked to storing thermal energy based on PV surpluses. Therefore, they include larger volume TES ($V_{TES}^{heat} \sim$ 7-9 m^3) that store at high temperatures ($T_{heat}^{low} \sim 55\,°C$ and $T_{heat}^{high} \sim 70\,°C$).

o PV generation and storage strategies dominate here.

- Cluster B: buildings with low S_{usab}^{dw} value (<10 m^2/dw)

Table 7
Normalization of optimized values of each building.

Building	S_{usab}^{dw} (m^2/dw)	$kgCO_2/S_{usab}^{dw}$ ($kgCO_2/\frac{m^2}{dw}$)	$E_{FromGrid}/S_{usab}^{dw}$ ($kWh/\frac{m^2}{dw}$)	$E_{PVtoLoad}/S_{usab}^{dw}$ ($kWh/\frac{m^2}{dw}$)
(02)1i-DE	43	23	77	263
(02)3i-C	30	42	157	340
(01)3c-C	14	151	523	1626
(04)2c-C	12	256	195	372
(03)1c-C	7	336	1029	2753
(01)1c-DE	7	2105	4538	13406

o Includes buildings with low available roof space, generally with high housing density.

o Retrofitting them using PV-HP-TES-ESS strategies, although with significant savings, is not as promising as previous cluster. These buildings will have (1) higher CO_2 emissions, (2) greater grid dependence, and (3) lower PV self-sufficiency.

o The control strategy focuses on the operation of the heat pump, which works at low temperatures ($T_{heat}^{low} \sim 30\,°C$ and $T_{heat}^{high} \sim 45\,°C$) with higher COPs. It is also linked to smaller TES tank volumes ($V_{TES}^{heat} \sim 6$ m^3).

o Strategies linked to the system overall performance dominate over renewable PV self-consumption.

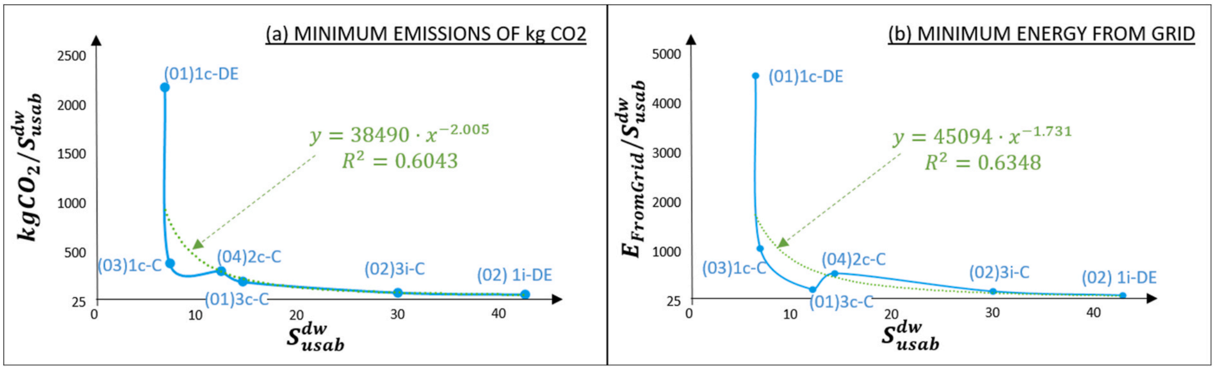

Fig. 11. Normalized annual indicators for (a) kg CO2 emissions and (b) grid electricity consumption.

- Cluster C: Buildings with intermediate S^{dw}_{usab} values. (10-25 m^2/dw).
  - o The rest of the buildings included in this range show intermediate values in the indicators evaluated.
  - o Different hybrid control strategies can be adopted, combining TES systems with the heat pump and PV self-consumption according to the specific situations of each building.

4.2.4. Preliminary economic analysis of investment by clusters

Although in the context of public rental housing the criterion of economic profitability is not considered a main priority, carrying out a preliminary economic analysis is important to implement any proposed rehabilitation action. The included cost functions are based on the CAPEX investment cost to obtain trends for each cluster applied to the optimized solutions of the six case studies. OPEX operating costs have not been included because they are assumed to have a proportional influence on all results, ranging between 1 and 3% of CAPEX/year depending on the equipment. If only the main investment components are considered, the total CAPEX cost is calculated as follows:

$$C_{tot} = C_{PV} + C_{HP} + C_{TES} + C_{EES} + C_{inv} \quad (6)$$

For simplified and approximate purposes, the following investment costs are considered:

- PV Panels (PV): The European CAPEX Benchmark is considered, related to the cost in Spain, between 1100-1600 €/kW.[1] Using $C_{PV} = 1300 \cdot P_{PV}$ [€].
- Heat pump (HP): Air-to-water heat pump 500-1000 €/kW[2], $C_{HP} = 750 \cdot P_{HP}$ [€].
- Batteries (EES): Li-ion battery 300-600 €/kWh,[3] $C_{EES} = 450 \cdot E_{bat}$ [€]
- Thermal Energy Storage (TES): A cost between 5 and 50 €/kWh is considered for the stored thermal energy.[3] Knowing that water is stored, $E_{kWh} = \rho \cdot V_{TES} \cdot c_p \cdot \Delta T / 3.6 \approx 1.16 \cdot V \cdot \Delta T$ and assuming a maximum temperature difference of $\Delta T \approx 70 - 55 = 15°C$. Therefore, the cost varies between 87 and 870 €/m^3. $C_{TES} = 480 \cdot V_{TES}$ [€]
- Inverter (INV): 150-250 €/kW,[4] $C_{INV} = 200 \cdot P_{PV}$ [€ /kWp]

Table 8 summarizes the total investment costs of the main equipment for each building analyzed. An inverse relationship is observed between the cost per dwelling (€/dW) and the useable solar area (S^{dw}_{usab}).

- Buildings included in Cluster A have an investment range for PV-HP-EES-TESS retrofitting of approximately 16,000-19,000 €/dw. This indicates that when the retrofitting potential is high, due to the high ratio between useable PV area and the number of dwellings, the unit cost per dwelling increases considerably. This means that buildings with high S^{dw}_{usab} capacity require a greater initial investment, especially in the PV + EES + INV solar renewable system. However, these cases are related to highly self-sufficient systems that are less dependent on the grid.
- Buildings in Cluster B require an initial investment of between 3000 and 5000 €/dw. This cost is more spread out as, even with lower self-consumption benefits, more dwellings are in use. This is due to the incorporation of fewer PV panels per dwelling and lower storage capacity, but greater dependence on the grid.
- Those in Cluster C have intermediate costs (between 6000 and 9000 €/dw), demonstrating a balance between self-consumption strategies and heat pump operation.

This preliminary economic analysis shows that investment depends, once again, on the dominant variable S^{dw}_{usab}. It indicates that achieving greater energy autonomy requires a higher investment cost.

4.2.5. Deviations in results if relevant parameters are modified

In general, when simulating the energy performance of buildings, sensitivity and uncertainty analyses serve to (1) identify the input variables that dominate the problem, (2) evaluate the uncertainty of the simulation against real-world values, and (3) improve the model and its calibration. However, these analyses are not as representative when the objective of the work is not related to the accuracy of the prediction in the simulation. In this work, on the contrary, the objective is to identify trends and optimal design strategies based on multi-objective optimization frameworks. Therefore, the aim is not to exactly reproduce the energy behavior of a particular system, but rather to establish strategies and define clusters based on the specific characteristics of the subsets. In this way, instead of seeking absolute numerical results, the goal is to find rules that establish generic system configurations and control strategies. In any case, these are the expected trends regarding variations in some of the most relevant parameters:

- Electricity and gas prices: These changes primarily affect economic performance rather than the system's physical behavior, as economic objectives have not been incorporated into the optimization problem. Therefore, these variations would not modify the system's control or design, only its economic interpretation.
- CO_2 emission factors: This change does affect one of the optimization objectives, although it is assumed that all solutions on the Pareto front would be affected almost proportionally. Therefore, the relative ranking of solutions and clusters would remain as described in the paper.
- The heat pump's COP: This coefficient influences the heat pump's electrical consumption. Previous work has concluded that optimization results remain robust when related to the system design, even

[1] solardataatlas.com.
[2] publicatio ….europa.eu.
[3] howtogosolar.org.
[4] Photovoltaic Storage Inverter - Highjoule.

Table 8
Preliminary economic analysis of the investment.

Building	*dw*	S_{usab}^{dw} (m^2/dw)	P_{PV} (kWp)	P_{HP} (kWp)	E_{EES} (kWh)	V_{TES}^{heat} (m^3)	C_{TOT} (€)	(€/**dw**)	*Cluster*
(02)1i-DE	20	43	141.8	50	267.12	6	377,874 €	18,894 €	A
(02)3i-C	11	30	54.7	70	100.8	9	183,465 €	16,679 €	A
(01)3c-C	40	14	95.6	185	181.44	6	362,208 €	9055 €	C
(04)2c-C	30	12	60.8	50	110.88	7	182,496 €	6083 €	C
(03)1c-C	39	7	45.9	110	85.68	6	189,581 €	4861 €	B
(01)1c-DE	171	7	187.8	260	352.8	7	635,210 €	3715 €	B

when performance varies. Ultimately, it is the operational conditions that change, not the system's structure. As with emission factors, the absolute values of system consumption from the grid or self-consumption would vary, but the system configuration would remain unchanged. This is because both the thermal storage volume and the control strategies are related to the unchanging demand.

- Climatic conditions: As justified, the case studies analyzed in this work are associated with real buildings located in defined sites with established climatic conditions. Therefore, varying the climatic conditions would only make sense to analyze behavior under future climate change scenarios or to compare specific regions. This climate change analysis has been addressed in previous works [52], which conclude that the optimized control setpoints remain unaffected by moderate climatic variations.
- Demand profiles: In this case, these demands also come from real, monitored, and representative data. While it is true that users affect system behavior and add uncertainty, this has already been addressed in the typology classification. Modifying these profiles does not add any physical significance to the research.

In this context, a sensitivity analyses can add new information but the computational load required does not justify the analysis. In this work, the objective is to obtain clusters and trends, not unique values. Sensitivity can be associated with the results that classify the outcomes based on the variable S_{usab}^{dw} and obtains generic results for heterogeneous situations.

5. Conclusions

This work defines a computational model with a holistic approach to optimize the design and control of hybrid renewable energy installations (PV-HP), with electrical energy storage (EES) and thermal energy storage (TES) on a macro scale, simultaneously optimizing the (1) reduction of CO_2 emissions, (2) minimizing grid consumption, and (3) maximizing PV self-consumption, as energy retrofit solutions. Unlike previous studies, which presented uncertainties in the estimation of energy demands, this approach incorporates a detailed model of thermal and DHW demand for each building. Besides, it customizes a generic simulation in TRNSYS, with advanced validated algorithms in MATLAB, and includes the design and control optimization for inertial components, ensuring an efficient solution adapted to the specific characteristics of each building.

The objective of this article is not to evaluate the performance of a known or predefined system based on variable control strategies. Rather, it is to simultaneously identify the optimal design and control values through a multi-objective optimization process. Thus, starting from a generic installation, the temperature thresholds at which the control responds and the thermal energy storage volume are determined. Therefore, the interactions between the components, the design, and the control are not fixed parameters but rather decision variables to be determined.

Thus, the model developed allows optimizing the refurbishment through PV-HP-TES-EES strategies on a building-by-building basis and the analysis of trends that can be extrapolated to other cases and building stock. To do so, specific data must be introduced into the model, which can be easily downloaded from public databases, and the model simultaneously simulates the building-installation ensemble and optimizes the design and control of the proposed refurbishment strategy. For that purpose, the code performs a parametric analysis, evaluating only the best set of combinations of the variables to be optimized within the search space and generating a database with the analyzed results. According to the results within the Pareto front, the point that represents the best set of values for minimizing annual CO_2 emissions, reducing grid electricity consumption, and maximizing PV self-consumption is chosen.

5.1. Conclusions on building-scale analysis

As an example of its application and the process development, a case study of a building coded as "(04)2c-C" is analyzed in detail. As justified, the optimization framework itself considers a wide variety of benchmarks with non-optimized solutions that serve to analyze the advantages of optimized design and control. Acordingly, the optimal three-dimensional point of this building refurbishment refers to the annual quantity of (1) $kgCO_2 = 3130$ kg, (2) $E_{FromGrid} = 2380$ kWh, and (3) $E_{PVtoLoad} = 4555$ kWh, which improves the performance of the system by up to 15% in terms of CO_2 emissions and 40% in self-consumption compared to non-optimized PV-HP-EES-TES refurbished configurations.

It is also inferred that the objectives to be minimized, namely (1) CO2 emissions and (2) grid consumption, are closely linked, which suggests modifying one of the two objectives for one related to economic variables.

Additionally, the consistency of the simulation model has been validated based on the obtained optimization results, and it has been shown that the SH and DHW energy demands are fully met under the established control criteria.

5.2. Conclusions on macro-scale analysis

Besides, the overall results of six representative buildings of six different typologies inside the public rental housing stock in the BAC are also shown throughout this work. The results allow identifying trends to be extrapolated to 40% of the stock analyzed, i.e.: 2344 dwellings. In this context, to extrapolate the results to these 48 buildings, a direct numerical scale is not used. Instead, patterns and relationships between the optimized control and design variables are identified. This approach proves to be more coherent and robust when the analyzed stock is heterogeneous. The results demonstrate that:

- The dominant indicator for designing the design and control strategies is S_{usab}^{dw}.
- The buildings can be grouped into three regimes: low, medium, and high PV availability.

In this way, there is no single optimal solution. Instead, clusters are identified for implementing strategies and are related to available indicators calculated for the entire analyzed stock.

As said, analysis of the optimization results for these buildings shows that one of the key factors is the ratio between the available PV surface area and the number of dwellings "S_{usab}^{dw}", given that the absolute size of the buildings does not have such a significant influence. In this regard, the yearly results are normalized based on this indicator and two clear strategies are identified to be extrapolated to buildings in the same regime:

- On the one hand, the optimal design of buildings with high S_{usab}^{dw} is related to larger volume thermal storage tanks and high-temperature HP operation. This strategy is linked to the thermal use of PV surplus.
- On the other hand, buildings with low S_{usab}^{dw} values are designed with smaller heating thermal tanks and low-temperature HP heat generation. This strategy allows focusing on the thermal efficiency of the system and reducing grid consumption.

Besides, the optimized control of DHW circuit is conditioned by health regulations in all the buildings, whose upper limit is set by default and the lower limit depends on the heat pump's operating strategy.

It is true that extrapolating the results also entails an associated uncertainty. On the one hand, uncertainties are assumed due to intra-typological variations, where the user profile or operating conditions vary. Furthermore, some simplifications are assumed when modeling the building, which are related to uncertainties, as well as the specific factors of each installation, which can vary from one to another.

However, some of these sources of uncertainty have already been identified and addressed when defining the models. For example, real consumption data and monitoring campaigns were implemented to define the typologies. Likewise, standardized indicators were defined to analyze rehabilitation priority and potential. It should also be noted that the proposed optimization model is independent for each building under study, thus adapting to the specific characteristics of the analysis. Furthermore, it is important to emphasize that the results indicate optimal design trends and do not reflect exact predictions.

5.3. Replicability in other buildings

The main advantage of the integrated building-installation model lies in its replicability on a macro scale to renovate the centralized energy systems of the public rental housing stock in the BAC. As demonstrated, to replicate the rehabilitation model, it is simply necessary to identify the buildings susceptible to energy integration, as the specific variables to be incorporated are directly downloaded from predefined databases. From there, the global model adapts to the specific conditions and optimizes the PV-HP-EES-TES system based on the particular characteristics of each building.

The optimization process results in a series of design and control parameters that can be integrated into the initial inventory database to assist in decision-making at both individual and provincial or macro scales, even to define local energy policies. Ultimately, large-scale intervention can consider not only the improvement of the energy efficiency of each building but also the optimization of common infrastructures, such as the potential centralized management of energy.

Although this study focuses primarily on 128 public rental buildings, the principles and methodologies used could easily be extrapolated to the private housing sector. In fact, the proposed model aims to become a flexible and effective methodology for any type of residential housing susceptible to rehabilitation processes, whether public or private, promoting the transition towards a more sustainable and energy-efficient housing stock. Therefore, as a future line of research, the application of the analysis on a territorial scale is proposed, considering the whole public building stock in the BAC that presents technical feasibility. Additionally, it is proposed to incorporate advanced adaptive control strategies that introduce elements of operational uncertainty, allowing not only to optimize emissions, grid purchases and self-consumption but also to improve thermal comfort and social acceptance by users analyzing the economic feasibility of the proposed PV-HP-EES-TES installation for each case. Finally, it is necessary to address the issue of variability and incorporate adaptation strategies in order to analyze the fluctuations that may occur in certain economic parameters, energy usage patterns, or climatic conditions at the location under study.

CRediT authorship contribution statement

M. Garro-Aguilar: Writing – original draft, Visualization, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **A. Prada:** Validation, Supervision, Software, Conceptualization. **A. Hernandez-Arizaga:** Validation, Supervision, Conceptualization. **L.M. López-González:** Validation, Supervision. **A. Picallo-Perez:** Writing – review & editing, Visualization, Validation, Supervision, Formal analysis, Conceptualization.

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.

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Data availability

The data that has been used is confidential.

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