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Design and Modeling Renewable Energy Communities

A case study in Cagliari

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Acknowledgment

This research work is a thesis inserted within an internship in ENEA[1]. The aim is to test the effectiveness of Energy Communities (ECs) through modeling and testing different scenarios on a proposed building. The analyzed building is one of the pilot sites of LIGHTNESS[2], which is in Cagliari/Italy. The work also contributes to the usage of the IES[3] software that is intended to achieve more sustainable design goals through energy-efficient and low-carbon buildings.

I would thank the following collaborators for their continuous support and guidance throughout this study, by sharing their knowledge and experiences generously:

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[1] ENEA: Italian National Agency for New Technologies, Energy and Sustainable Economic Development
[2] Lightness: EU funded project for Horizon 2020 research and innovation program
[3] IES: Integrated Environmental Solutions
[4] R2M: Research to market solution, research and innovation company

Preface

Here I am, at the end of another journey in my life... I'm grateful to be part of this master program dealing with sustainability, which now is an imperative issue that we should all deal with, regardless of our different disciplines. In these challenging times, where the world is facing and adapting to a pandemic, it is important to learn from it by analyzing the impacts human beings have on this planet. Working on energy communities and energy transition made me more aware of the climatic actions we can take, adding a lot of information and references to my existing knowledge base.

I have performed my internship, which is part of this thesis, in ENEA. Being involved in an international project has built extra excitement and determination for me. Hence, this thesis provided me with a lot of experience, first by investigating a new study field, secondly by working collaboratively with diverse disciplines. I would like to thank my supervisors in ENEA, Mattia Ricci and Francesco Baldi, for their continuous support and time throughout the whole process. Their effort in conducting this work is invaluable for me.

I would also like to send my gratitude to my supervisor Prof. Guglielmina Mutani, for her guidance and in-depth feedback during the process. She was always generous by sharing her knowledge and references that supervised me and helped in making the best of this work.

Considering the period in which I was working on my thesis, I had moments when I felt exhausted, which is also linked to the complexity and amount of data this study had. At those moments, my brothers Kadir and Mahir were always there to cheer me up and motivate me. I would also thank my dear friend Eme for the continuous moral support and positive energy she gave me in my weary times.

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Abstract

In the last decades, European countries shifted towards decentralized energy generation, which is a crucial step for enhancing the diffusion from centralized power systems to smaller-scale systems. These small-scaled systems include local energy communities (ECs). The renewable energy communities (RECs) have a significant role and potential in this energy shift. Starting from the fact that using renewable energy sources (RES) reduces greenhouse gas emissions and the dependence on fossil fuels, the RECs are effective bodies, in means of scale and management, for the implementation of sustainable urban territories.

This work analyzes different EC scenarios, considering energetic and economic perspectives. The energy concern is associated with improving the self-consumption and self-sufficiency indexes, while the economic concern is associated with the received incentive for each designed EC. The analyzed case study is in Cagliari/Italy, a typical condominium of eight apartments with a low energy rating (G). The study also covers the energy efficiency improvement associated with the retrofit intervention which is conducted during the research process. The analysis scale includes both the share of energy between the eight apartments of the condominium and an EC composed of the studied building with neighboring buildings.

The objective of this work is to contribute to the research studies and EC applications providing an illustrative model, with numerical data and alternative scenarios, to give detailed analyzes that can be used for the implementation of different sized ECs, and to demonstrate the significant role ECs can play in moving towards decentralized energy generation.

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Introduction

Project description

The analysis in this work is based on the European LIGHTNESS[1] research and innovation program H2020, which aims to design renewable energy communities (RECs) and test their effectiveness through numerical modeling. The goal is to make the European energy sector more sustainable and democratic by empowering citizens to generate, share and sell renewable energy, one of the most practical contributions in the energy transition.

The case study analyzed in this work is one of the five pilot sites of LIGHTNESS (Italy - Cagliari), which focuses, first, on building-scale analysis and the energy share between the common uses and the eight apartments, then replicating the building to create a district-scale energy community (the share of energy from the main analyzed building with one neighboring building). The work involves different parties that work collaboratively for the fulfillment of the project's objective. ENEA[2] has the role of testing the ICL platform (Intelligent Communities Lifecycle) by applying it to the pilot cases in the project, together with defining alternative implementation scenarios. R2M[3] is the general project coordinator, in addition, they are responsible for the Italian pilot; thus, they are in charge of providing data and information used in this work to create the appropriate connection with the pilot. ILECO[4], the leaders of the other two pilots (Poland and The Netherlands), and are the responsible partner for the practical implementation of the energy communities in the project. The IES-VE software team, the developers of the ICL platform, are also included in this work as an assisting team for the software utilization.

Thesis statement

Together with the project team's objectives, this thesis aims to contribute to the research studies that analyze and focus on possible methods for the implementation of Energy Communities (ECs). The numerous studies include the importance of shedding light on energy transition and its role in lowering the total global emissions. Furthermore, the increasing demand for energy and the extensive use of fossil fuels urged the shift towards more sustainable and clean energy sources. Together with being responsible for the major energy consumption, the building sector has great potential for this transformation. Energy communities can play a key role in the shift from decentralized energy systems to more local generations. The community of this work is composed of the common uses of the condominium and the eight apartments for the building-scale community and two neighboring condominiums for the second scale community.

The study follows a bottom-top approach that evaluates a single apartment's hourly consumption using detailed profiles. These analyses provide a perception of the different consumption trends of each apartment, e.g., heating, cooling, and DHW, which will be conducted later in the RES implementation. The study includes a basic understanding of the different parameters that affect a single apartment's energy consumption, the building's energy profile, and the effect of the building envelope on its overall energy consumption. It also includes understanding and analyzing the available technologies for generating and managing energy from renewable sources and testing their effectiveness considering economic, environmental, and energetic results of the simulated scenarios.

Chapter 1 reviews and interprets some related literature that introduce the core motivation of this work. This is followed by explaining the methodology followed in performing this study in Chapter 2. Chapters 3, 4, and 5 provide information about the analyzed case study, the inputs, scenarios, and results. Finally, the work is concluded by discussing the outcomes and developing assumptions in chapter 6.

[1] Lightness: EU funded project for Horizon 2020 research and innovation program (https://www.lightness-project.eu/pilot-sites/)
[2] ENEA: Italian National Agency for New Technologies, Energy and Sustainable Economic Development
[3] R2M: Research to market solution, research and innovation company
[4] iLECO: international team that focus on the future expected network structure of "local energy communities"

About The Software

The tool used to simulate and analyze the energy performance in this work is IES-VE (Integrated Environmental Solutions - Virtual Environment). This collaborative tool allows to share the data among different disciplines (e.g., engineers, architects, contractors). It also allows analyzing energy communities by sharing info with the integrated software (iVN, iCD, iSCAN). IES-VE is used either for the early design phases, to perform a bioclimatic architecture (e.g., optimizing building position considering the local climate, predicting the inner space's daylight factor, ventilation, etc.), or for the refurbishment of existing buildings to enhance their energy consumption, add renewable sources and simulate the new case comparing it with its previous situations.

In this work, VE is used for modeling and simulating the case study building in order to:

- Verify the total consumption in the simulated model with the actual data from available bills.
- Compare the consumption of the building before and after intervention works.
- Export the hourly data obtained for each apartment/building to be used in iVN for the energy community analysis and scenarios.

VE helped in obtaining a realistic model due to its ability to define user profiles. It was possible to set profiles for each apartment based on the available data to reflect actual occupation, which helps to create various real-life scenarios. The daily and weekly profiles are essential for a residential project since the user behaviors differ among the apartments during a whole day, which is also an essential indicator for choosing the most appropriate scenario for the energy community. iVN (Intelligent Virtual Network) is used for designing the distributed energy network of the community. It is possible to model, compare and optimize the design and management of electricity, heating, cooling, renewable energy sources, etc. The diagram below gives, in brief, the general workflow considering the used software:

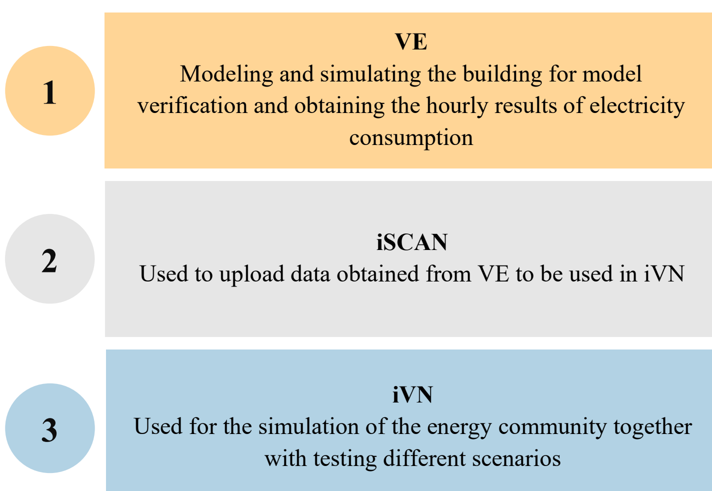


Figure 1 software workflow

1. Literature review

1.1. The shift towards decentralized energy generation

In the last decade, European countries shifted towards decentralized energy generation, which is a crucial step for enhancing the diffusion from centralized power systems to smaller-scale systems. It involves a turn from fossil fuel delivering electricity to more sustainable generations, which helps to tackle climate change. The distributed energy (on-site generation) produced by small systems reduces the transportation cost and system losses since they are generated close to the consumption points. This in turn has both environmental and economic benefits. It also has social benefits since it involves small-scale producers, providing new employment and small-scale businesses. This action is strengthened with the publication of the energy rule book Clean Energy for all Europeans Package (Clean Energy for All Europeans, 2019). The benefits in the package concern consumer, environmental and economic perspectives. It includes different acts, like energy efficiency and energy performance enhancement.

Energy efficiency, which is among the most prominent objectives of Clean Energy for All Europeans, means taking action to consume less energy for a process, which plays an important role in reducing greenhouse gas emissions. It has also economic benefits, such as reducing energy consumption and cost. The EU had a target of reaching 20% energy efficiency by 2020 (The Energy Efficiency Directive, 2012).

Enhancing the energy performance of a building is another crucial matter since the construction sector is among the biggest consumers of energy. They account for 40% of energy consumption and 36% of CO2 emissions in the EU (Clean energy for all Europeans, 2019). Thus, enhancing the energy performance is accountable for reducing the greenhouse gas emissions, which contributes to meet the EU target in reducing greenhouse gas emissions, at least 40% by 2030 compared to 1990 (EU 2018/844).

1.2. Community involvement in the energy transition

This shift towards decentralized energy generation led to the active involvement of citizens in this practice, which allowed the inclusion of the local communities. Energy Communities (ECs) are among the most effective components in this implementation. They adopted a significant role over the last decade, proposing new opportunities for citizens to be involved as active members in the energy transition. Among the aims of ECs is lowering the CO2 emissions and the reliance on fossil fuels to minimize the carbon footprint of the individuals. The scale of ECs makes them potential members that can be scaled to urban practices, which in turn will become part of the national energy movement. These communities can operate on the new future of their environment and cities. There are different names for these citizen-driven projects (Radwanska, 2019), each differs slightly in the arrangement, e.g., Local Energy Communities, Citizen Energy Communities, Renewable Energy Communities.

The Renewable Energy Community (REC) will be the used theme in this research. RECs have a significant role in the energy transition. Starting from the fact that using renewable energy sources reduces greenhouse gas emissions and the dependence on fossil fuels, the RECs are effective bodies, in means of scale and management, for the implementation of sustainable urban territories. The EU has also set an ambitious, binding target of 32% for renewable energy sources in the EU's energy mix by 2030 (2018/2001/EU).

1.3. The motivations behind citizen involvement in ECs

The motivations behind the citizen involvement in these practices are generally concerned with social and environmental aspects. S. Soeiro and M. Ferreira Dias (2020) analyzed the main motivations beyond citizen participation in this action by questioning two points: the *willingness* of citizens to participate, and the *factors* that influence their motivations to participate. They do this by a systematic review of existing references on ECs, together with some questions for more than 400 energy communities. The sense of community that is enhanced with this practice is among the major drivers in the involvement of these people. It also shows that this investment which promotes a more sustainable environment is another important driver for ECs. The environmental benefits of decentralized energy production lie behind minimizing carbon footprint and greenhouse gas emissions, which citizens are now more concerned about climatic issues.

The economic gain achieved in ECs is also among the motivations for citizen involvement, but compared to the aforementioned aspects, they are less considerable. Economic drivers exist, but the concerns related to energy policies are more dominant because people follow social and moral norms since they are not always followed by self-centered incentives (Bauwens, 2016).

1.4. Urbanization and energy consumption increase

More than half of the world's population lives in urban areas. The overtaking of the urban population number occurred firstly in 2007, and it has been going on ever since (UN, The World's Cities in 2018). The urbanization process in shifting from rural to urban areas will continue to grow, and this leads to new governance models for sustainable cities being developed. An example of this is Masdar City in Egypt, one of the world's most sustainable urban communities (M.M. Fouad, et al., 2020). There are plenty of examples regarding actions taken in the building sector, following this continuous urbanization across the globe.

1.5. The building sector in energy consumption

The building sector, which is accountable for the major energy consumption, makes a quite good ground for the practices of ECs. Only in China, about 2 billion new square meters have been added each year during the last decade (Delmastro, et al., 2015). This shows that the energy demand for the building sector will not decrease, and we should seek for behavioral change to limit the consumption. The situation is the same across the world, with the difference that some European countries retain a stock of existing buildings instead of newly added ones. Germany, Italy, and France have the largest number of dwellings across Europe (EU Buildings Database).

These data indicate that the building sector can play a prominent role in reducing energy consumption across the globe since they are the major consumers. With a closer look at the type of buildings and their related energy consumption, we can see that residential buildings are the predominant consumers. In 2018, the residential sector represented 26.1 % of final energy consumption in the EU (Eurostat).

Figure 2 illustrates the final energy consumption by fuel in the residential sector in the EU. It demonstrates that natural gas and electricity are the most consumed energy type in the residential sector. In Table 1 we can see further the energy consumption in households by type of end-use. As illustrated in Figure 3**,** heating accounts for 63.6 % of final energy consumption, lighting 14.1%, water heating 14.8%, cooking devices 6.1%, space cooling 0.4%, and the other end-uses cover 1%. Thus, space and water heating account for 78.4 % of the final energy consumed by households.

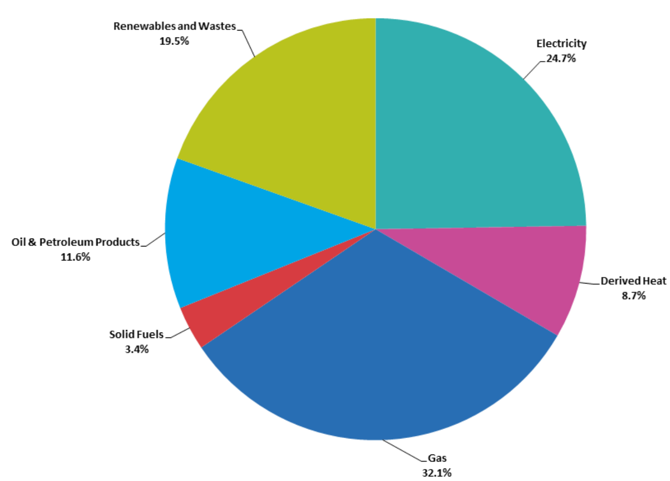


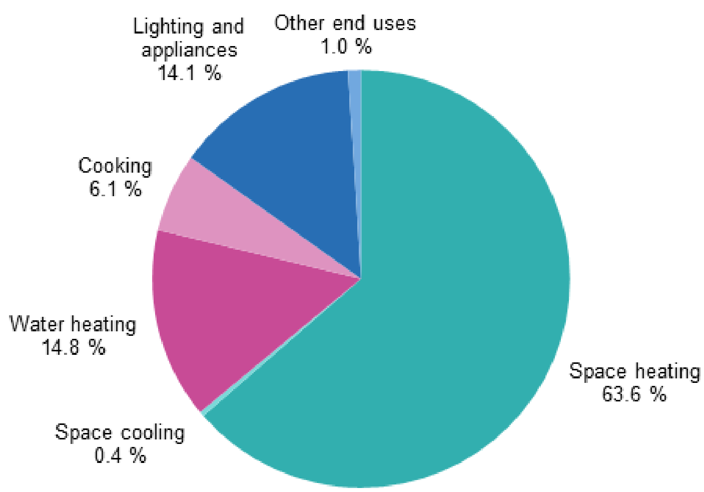
Figure 2 Final energy consumption in the residential sector by fuel, EU-27, 2018

EU-27	Total Residential /Households	Space heating	Space cooling	Water heating	Cooking	Lighting and appliances	Other end uses
Electricity	24.7	3.3	0.4	3.0	3.0	14.1	0.8
Derived Heat	8.7	6.7	0.0	1.9	0.0	0.0	0.0
Gas	32.1	24.2	0.0	6.0	1.9	0.0	0.0
Solid Fuels	3.5	3.2	0.0	0.3	0.0	0.0	0.0
Oil & Petroleum Products	11.6	9.0	0.0	1.7	0.8	0.0	0.1
Renewables and Wastes	19.5	17.2	0.0	1.9	0.3	0.0	0.1
Total	**100.0**	**63.6**	**0.4**	**14.8**	**6.1**	**14.1**	**1.0**

Source: Eurostat (online data code: nrg_d_hhq)

eurostat

Table 1 Share of fuels in the final energy consumption in the residential sector by type of end-use, 2018 (%)



Source: Eurostat (online data code: nrg_bal_c)

eurostat

Figure 3 Final energy consumption in the residential sector by use, EU-27, 2018

The illustrated numbers demonstrate that the residential buildings can be used as potential models in creating effective ECs, since the overall consumption is high in these buildings. The aim is to find sustainable solutions to reduce the dependency on fossil fuels, thus reducing greenhouse gases, which will contribute to the reduction in carbon footprint related to human activities.

1.6. Renewable energy sources as potential incentives for ECs

Renewable sources are the reference to energy generation in most real cases (S. Moroni et al., 2019). They are big drivers for decentralized energy generation and allow the diversification of energy production, reducing the use of fossil fuels. In the recast of the Renewable Energy Directive II (RED II), the EU raised its target for Renewable Energy Sources consumption by 2030 to 32%. Another objective, which is behind European Green Deal (COM(2019) 640 final), is to become the world's first climate-neutral continent by 2050. This will enable European citizens and businesses to benefit from a sustainable green transition.

The difficulties in using renewable sources are related to the land-use plan and the building codes (S. Moroni et al., 2019), which put restrictions on the activities of the small-scaled and place-based communities. By removing the barriers and moderating the restrictions in using renewables, these small communities will be encouraged to practice the local production of their energy.
The most used RES is wind power (Eurostat: Renewable energy statistics). Wind and hydropower accounted for 35% for each of the total electricity generated from renewable sources. The remaining 30% of electricity generated was from other three sources: 13% solar power, 8% solid biofuels, and 9% from other renewable sources.
Solar power is the fastest-growing source, rising from 7.4 TWh in 2008 to 125.7 TWh in 2019 (Eurostat, 2019). This shows the high potential in solar energy for initiating the small-scaled RECs.

1.7. Photovoltaic panels as the major source for ECs of residential buildings

The decrease in the costs of Photovoltaic Panels during the last years made solar power among the most used renewable energy sources for these communities (J.M. Roldan Fernandez et al. 2021, A. Radwanska, 2019). The wide range of PV panel types also allows the choice of the best option for an investment, ensuring the consumption targets and economic feasibility. Architects and engineers are integrating PV panels in their initial design decisions, which created Building Integrated Photovoltaics (BIPV) (M.M. Fouad, et al., 2020). They act as construction material and energy producers.

There are architectural concerns regarding the BIPV, but still, they are more preferred since it is possible to estimate the visual impacts of these panels and their design integration. Architecturally, these building-integrated panels are replacing the traditional envelope materials, thus combining technological devices with architecture for more sustainable building stock. The integrated panels are replacing the subsequently added panels, which are not visually appealing. This practice is economically more cost-efficient since it eliminates the use of envelope materials and PV panels separately.

The EU countries helped in promoting policies to assist the self-consumption of renewables. In Italy, the government introduced measures that allow the residential and commercial bodies to install PV panels for their entities, to generate their own electricity, together with selling the surplus to the grid. The general and substantial incentives for the use of the PV panels are directly related to the regulations applied by the involved government.

The Directive (EU) 2018/2001 also expressed that there should be a new definition for the *renewables self-consumers* and the need to establish a regulatory framework to empower them to generate, consume, store, and sell without irrational loads.

The photovoltaic sector in Europe accounted for robust growth over the last decade. The PV sector in Italy, together with Germany, became one of the main European markets in 2010-2013 (Spertinoet al., 2013). This shows the big influence of PV panels, especially in the residential sector which accounted for 85% of the new PV installations (Abdin & Noussan, 2018).

There are abundant applications of ECs using solar power and PV panels, achieving the designated self-sufficiency and self-consumption ratio. *Self-sufficiency* is defined as the ratio between the locally produced and used energy and the total energy consumption, whereas *Self-consumption* indicates the ratio between the locally produced and used energy and the total PV production (Todeschi, et al., 2021).

In Italy, according to the report by the Energy services management, *(Gestore dei Servizi Energetici),* the self-consumption average reached 29% (GSE, 2017). The provided numbers show the promise and potential of using PV panels in implementing the ECs.

The self-consumption ratio is an important indication to initiate an EC. It should be high enough to avoid the excess of produced energy, which creates inconvenience in selling or storing it. Selling the surplus energy to the grid still needs to be more planned and customer-oriented. The storage systems are not profitable yet, due to the high prices of battery storage (Abdin & Noussan, 2018; Fernández et al., 2021). These inconveniences in selling and storing the surplus lead to the necessity of optimizing the self-consumption ratio in the planned EC to achieve economic feasibility, which in turn will increase the request for the involvement.

Some studies analyzed the profitability of PV panels, especially in residential buildings. The study of Lazzeroni et al. (2020) examined two scenarios, considering the regulatory framework of Italy. In the first scenario, the achieved profitability is positive with small-sized PV installation (1.2 kWp). In the second scenario, the cost of PV assembly and maintenance is assumed to be covered by an energy provider, who in turn sells part of the PV generation. The second scenario showed positive profitability only if the energy consumption of the customer is higher than the Italian average for residential users.

Another study by Bertsch et al. (2017) investigated the drivers for the profitability of PV investments in households using techno-economic simulations.

The results showed that the profitability depends on various drivers, for example, PV costs, the availability of FIT, the number of households, and electricity retail prices, which are more important variables for combined PV-storage systems. The case of Germany is more profitable than Ireland due to the fact that the current market conditions and regulations in Germany are better. Generally, the incentives and profitability for investing in PV combined with storage systems will increase in both countries when the costs of storage systems decrease. However, the self-sufficiency rate of 75% for Germany, 65% for Ireland can be achieved for the most profitable combinations of PV and storage systems. Increasing the self-sufficiency ratio further will not be concluded with a profitable investment.

The study of J. Liu et al. (2021), which analyzed hybrid systems, also indicated better results in self-consumption ratio with the presence of battery storage systems, since they avoid the inconvenience of electrical load when storing the surplus generation.

The overall scenarios which analyzed the investment options, with and without storage systems, showed better results obtained when using PV-storage combined systems. The fact is the presence of storage systems reduces system disturbance, which results in preferable economic feasibility and better flow of energy within the community.

1.8. Definition of terms

TERM	DEFINITION	REFERENCE
Adjustment Factor	quantifiable parameter affecting energy consumption ex.: Weather conditions, behavior related parameters (indoor temperature, light level) working hours, production throughput, etc.	*EN 16247-1:2012*
Citizen Energy Community	a legal entity that: a. is based on voluntary and open participation and is effectively controlled by members or shareholders that are natural persons, local authorities, including municipalities, or small enterprises. b. has for its primary purpose to provide environmental, economic, or social community benefits to its members or shareholders or to the local areas where it operates rather than to generate financial profits; and c. may engage in generation, including from renewable sources, distribution, supply, consumption, aggregation, energy storage, energy efficiency services or charging services for electric vehicles or provide other energy services to its members or shareholders;	*Directive (EU) 2019/944 of the European Parliament*
Distributed Generation	generation plants connected to the distribution system where the distribution system is the high-voltage, medium voltage and low-voltage network as opposed to the extra high-voltage and high voltage transmission system	*Directive 2009/72/EC of the European Parliament*
Energy Audit	a systematic procedure to obtain adequate knowledge of the existing energy consumption profile of a building or group of buildings, of an industrial operation and/or installation or of a private or public service, identify and quantify cost-effective energy savings opportunities, and report the findings.	*Directive 2006/32/EC of the European Parliament*
Energy Audit	systematic inspection and analysis of energy use and energy consumption of a site, building, system or organization with the objective of identifying energy flows and the potential for energy efficiency improvements and reporting them	*EN 16247-1:2012*
Energy Efficiency	a ratio between an output of performance, service, goods or energy, and an input of energy	*Directive (EU) 2006/32/EC of the European Parliament*
Energy Efficiency	ratio or other quantitative relationship between an output of performance, service, goods or energy, and an input of energy Ex.: Conversion efficiency; energy required/energy used; output/input; theoretical energy used to operate/energy used to operate.	*EN 16247-1:2012*
Energy Efficiency Improvement Measure	amount of saved energy determined by measuring and/or estimating consumption before and after implementation of one or more energy efficiency improvement measures, whilst ensuring normalization for factors that affect energy consumption	*EN 16247-1:2012*
Energy Performance Indicator	quantitative value or measure of energy performance, as defined by the organization	*EN 16247-1:2012*

Energy Performance of a Building	the calculated or measured amount of energy needed to meet the energy demand associated with a typical use of the building, which includes, inter alia, energy used for heating, cooling, ventilation, hot water and lighting.	*Directive 2010/31/EU of the European Parliament*
Nearly Zero-energy Building	a building that has a very high energy performance, as determined in accordance with Annex I. The nearly zero or very low amount of energy required should be covered to a very significant extent by energy from renewable sources, including energy from renewable sources produced on-site or nearby.	*Directive 2010/31/EU of the European Parliament*
Photovoltaic Panel	A PV panel is basically a solid-state semiconductor device that converts light energy into electrical energy.	*Solar Heating and Cooling Systems, 2017*
Renewable Energy	energy from renewable non-fossil sources, namely wind, solar (solar thermal and solar photovoltaic) and geothermal energy, ambient energy, tide, wave and other ocean energy, hydropower, biomass, landfill gas, sewage treatment plant gas, and biogas.	*Directive (EU) 2018/2001 of the European Parliament*
Renewable Energy Community	a legal entity: a. which, in accordance with the applicable national law, is based on open and voluntary participation, is autonomous, and is effectively controlled by shareholders or members that are located in the proximity of the renewable energy projects that are owned and developed by that legal entity. b. the shareholders or members of which are natural persons, SMEs or local authorities, including municipalities. c. the primary purpose of which is to provide environmental, economic or social community benefits for its shareholders or members or for the local areas where it operates, rather than financial profits;	*Directive (EU) 2018/2001 Of The European Parliament*
Renewables Self-consumer	a final customer operating within its premises located within confined boundaries or, where permitted by a Member State, within other premises, who generates renewable electricity for its own consumption, and who may store or sell self-generated renewable electricity, provided that, for a non-household renewables self-consumer, those activities do not constitute its primary commercial or professional activity	*Directive (EU) 2018/2001 of the European Parliament*
Self-consumption *(SC/P)*	Is defined as the ratio between the energy production that is locally used *(SC)* and the total PV production *(P)*	*(Todeschi et al., 2021)*
Self-sufficiency *(SC/C)*	Is defined as the ratio between the energy production that is locally used *(SC)* and the total energy consumption *(C)*	*(Todeschi et al., 2021)*
Smart Metering System	means an electronic system that is capable of measuring electricity fed into the grid or electricity consumed from the grid, providing more information than a conventional meter, and that is capable of transmitting and receiving data for information, monitoring and control purposes, using a form of electronic communication.	*Directive (EU) 2019/944 of the European Parliament*
Solar Collector	a device that collects and/or concentrates solar radiation from the Sun. These devices are primarily used for active solar heating and allow for the heating of water for personal use	*G. Boyle. Renewable Energy: Power for a Sustainable Future, 2nd ed. Oxford, UK: Oxford University Press, 2004*

Table 2 Definition of terms

1.9. Nomenclature

NOMENCLATURE	
CECS	Citizen Energy Communities
CSC	Collective Self-Consumption
DHW	Domestic Hot Water
DSM	Demand Side Management
EC	Energy Communities
EER	Energy Efficiency Ratio
EPG	Energy Performance Gap
HDD	Heating Degree Days
NZEB	Nearly Zero Energy Buildings
OP	Over Production
PI	Piping and Instrumentation
POD	Point Of Delivery
REC	Renewable Energy Community
RES	Renewable Energy Source
SC	Self Sufficiency
SCI	Self-Consumption Index
Scop	Seasonal Coefficient of Performance
SMS	Smart Metering System
SSI	Self-Sufficiency Index
TC	Total Consumption
TMY	Typical Metrological Year
TP	Total Production
UD	Uncovered Demand
WWR	Window to Wall Ratio
ZEB	Zero Energy Building

Table 3 Nomenclature

2. Methodology

This study aims to design and analyze an energy community in Cagliari, which is one of the pilot sites of the EU LIGHTNESS project. The community consists of eight apartments located within the same building: a typical Italian condominium. The main interest will be analyzing this small-scaled community by testing different scenarios that target achieving the most feasible self-consumption and self-sufficiency indexes. This will be followed by expanding the community to involve neighboring condominiums and analyzing both the economic and environmental impacts of the EC. The analyzes focus on testing the effectiveness of ECs through numerical modeling.

The understanding of EC scope is supported by reviewing some of the available literature, applied examples, and policies, which provided a comprehensive investigation in EC.
The methodology followed in this work demonstrates a bottom-top approach, where the single apartment has taken as the starting point of the community. The hourly consumption profiles form the core energy demand for each member of the community.
The study begins with a quantitative method: using on-site collected data in modeling the building. The available electricity bills of four apartments are used to verify the model; this is implemented following the energy audit described in the European standard UNI CEI EN 16247-2:2014. Chapter 4 illustrates in detail the followed steps that aim to reduce the energy performance gap, which occurs in case of a discrepancy between the design and the actual operation. Following the model validation, the renovation works conducted by R2M are inserted into the verified model to achieve the base model of the EC. The defined scenarios in chapter 3.3 are tested on the retrofitted building. The study is concluded by analyzing the different motives and results of each simulated scenario.
Besides the EC modeling and simulation, which are the main objective of the research, this work also provides in detail the inputs and results of the used models (before and after renovation), which gives an important insight into the energy consumption profiles of a single apartment. These detailed inputs/outputs present an important understanding of the variables that affect energy consumption within an apartment, which in turn is reflected in the energy consumption of the whole building.
These variables allow for a more reliable construction of EC. It can also contribute to future works that examine hourly energy consumptions, user behaviors, RECs, and any related issues.
Figure 4 briefly illustrates the mentioned methodology workflow.

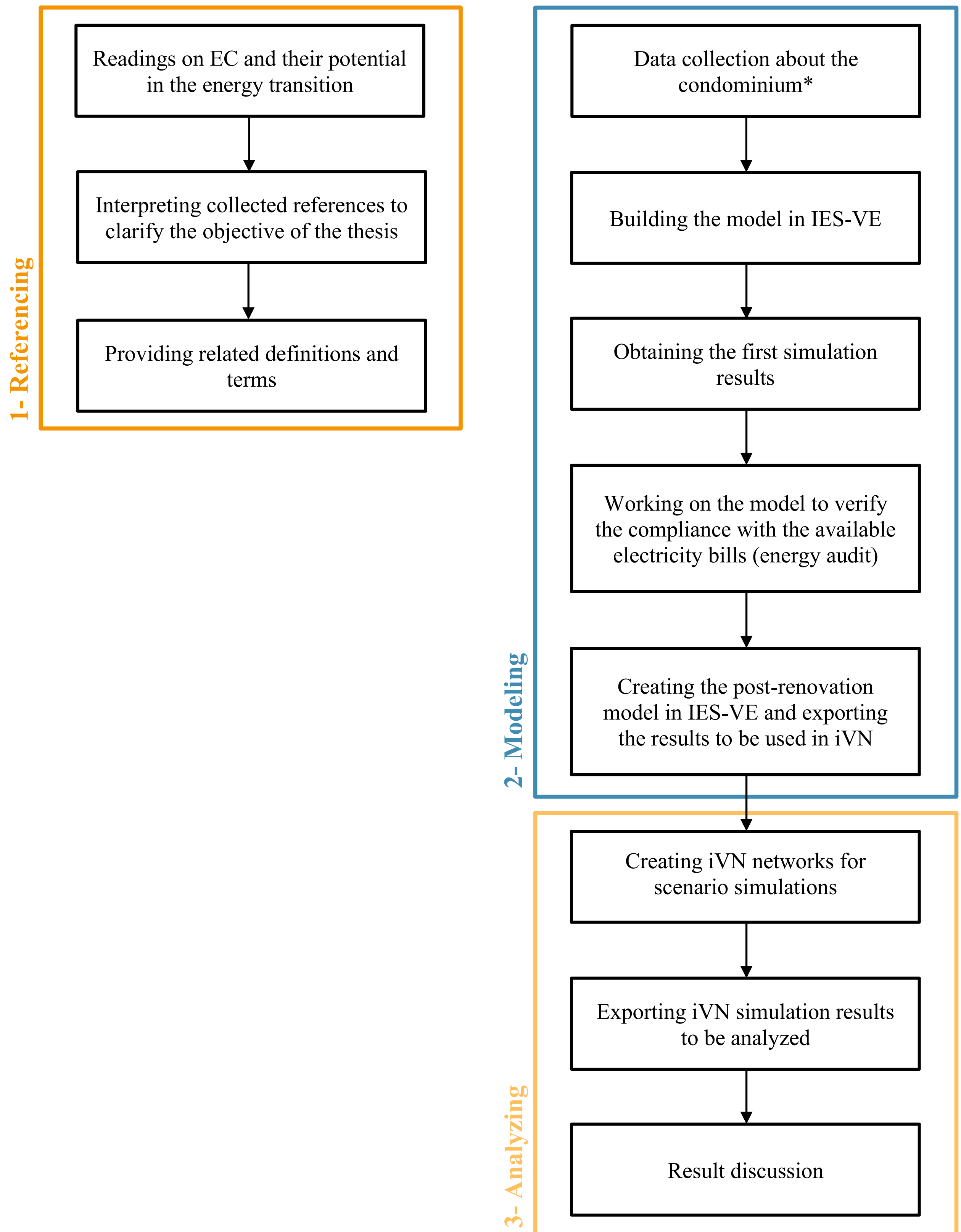


Figure 4 Methodology workflow

3. The case study of Cagliari

3.1. About Cagliari

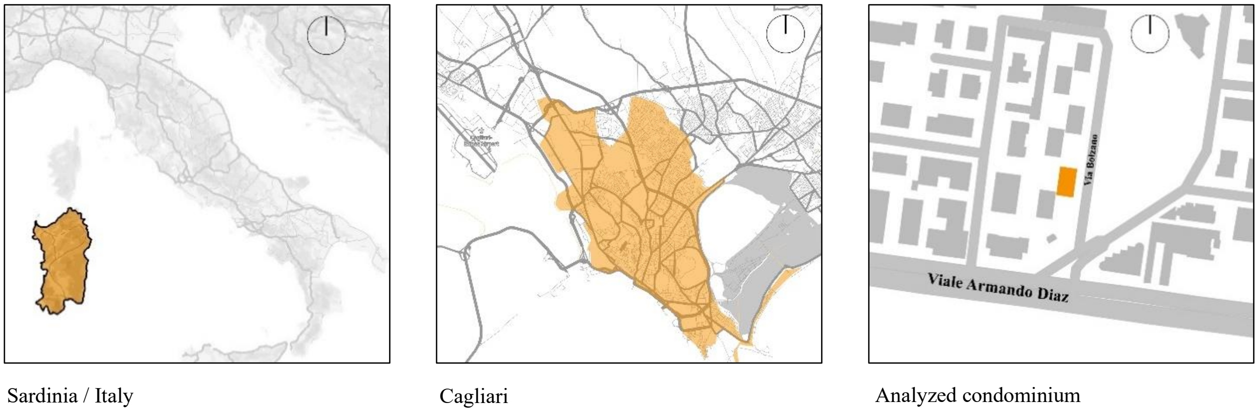


Figure 5 Project location

The building is located in Cagliari, the capital city of Sardinia and the most populous municipality on the island. It is considered Sardinia's economic and industrial hub, having one of the biggest ports in the Mediterranean Sea and an international airport. There is dense urbanization in Cagliari, making it a metropolis surrounded by depopulated rural areas, resulting in the concentration of economic activities in Cagliari. This concentration also resulted in an imbalance in the territorial distribution of Sardinia's population; more than a quarter of the population is concentrated in Cagliari. Since 1951, the population density of Cagliari has risen from 164 to 339 inhabitants per km² (Istat 2019). Considering 2019, the year in which the case study simulations were considered, the population of The Metropolitan City of Cagliari (17 communes) was 422.840, where the people of the municipality of Cagliari were 151.005 inhabitants. It is dominated by the old population; the population aged 65 and over is 23% on 1st Jan 2020 (Istat). The energy in Sardinia is not connected to the distribution network of methane, its major households gas, with a percentage of 80.8, is gas purchased in cylinders, 7.3% connected to LPG, 10.7% installed outside with periodic replenishment (Istat 2019).

3.1.1. Climatic condition

Cagliari has hot summers and mild winters, with an average temperature of 17.5 °C. The hottest month is August, with an average temperature of 26.4 °C, and the coldest is February, with an average temperature of 10.1 °C. The Climatic zone of Cagliari is C; there are six zones in Italy: A, B, C, D, E, F (A hottest, F coldest), (Decreto del presidente della Repubblica n. 412 del 26 agosto 1993 (tabella A).

- Heating system: November 15th - March 31st (10 hrs/day)
- Degree days 990*

*Degree days: unit measurement shows the need to turn on the heating system to reach the threshold of 20° C (the highest the number, the more demand for the heating system)

3.1.2. Building's status quo

The building, which is located in the Bonaria neighborhood, is a typical Italian condominium built in 1966, consisting of eight apartments distributed on four floors (including the raised ground floor). The vertical opaque structure (exterior walls, staircase wall) is made of Pietra Cantone (sandstone), a traditional construction material of the area.

Each apartment has an individual autonomous heating/cooling system, and a boiler system for DHW (except for apt 3 and 5). The current energy class is G, with no envelope insulation (except for some partial insulation of 5cm for apartment 6, on the northern wall, and poor roof insulation). Below is the stratigraphy of the building components before the renovation work:

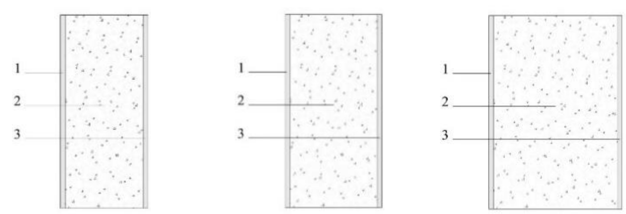
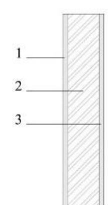
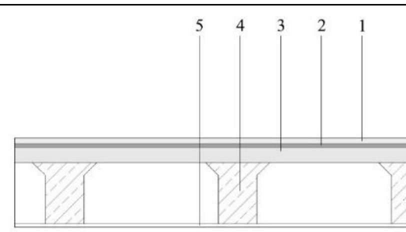
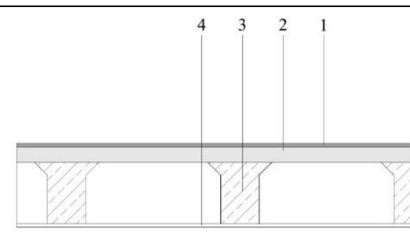
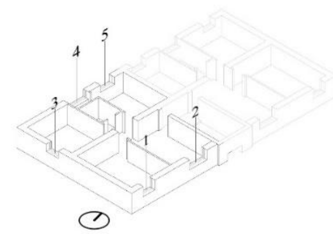
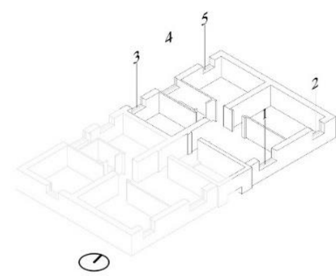
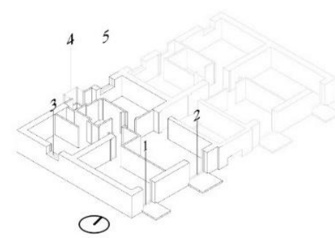
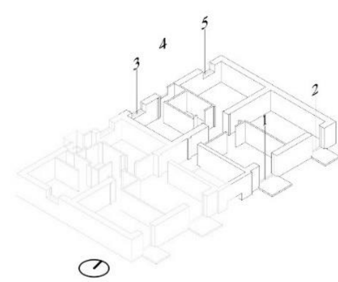
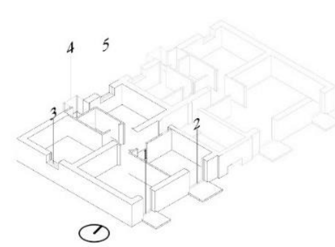
COMPONENT'S STRATIGRAPHY		
Exterior walls	1- Plaster 2 cm 2- Sandstone wall 40/25/22 cm 3- Plaster 2 cm	 22cm: veranda walls 25cm: staircase walls 40cm: exterior walls
Interior walls	1- Plaster 1.5 cm 2- Brick wall 10 cm 3- Plaster 1.5 cm	
Floors	1- Ceramic tiles 1 cm 2- Mortar 1 cm 3- Cement floor 4 cm 4- RCC hollow brick slab 16 cm 5- Gypsum board 1 cm	
Roof	1- Water insulation 0.5 cm 2- Cement floor 4 cm 3- RCC hollow brick slab 16 cm 4- Gypsum board 1.5 cm	

Table 4 building's pre-renovation component stratigraphy

WINDOWS		
Apt	**Frames**	**Axonometric floor plans**
Apt 1 – ground floor	All wooden frames	
Apt 2 – ground floor	All wooden frames	
Apt 3 – first floor	All PVC frames	
Apt 4 – first floor	All PVC frames	
Apt 5 – second floor	1- wooden frame 2- wooden frame 3- PVC frame 4- aluminum frame 5- PVC frame	

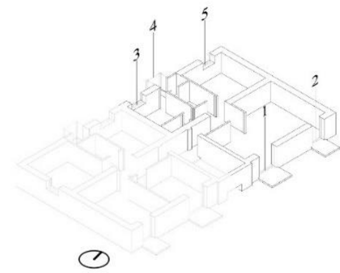
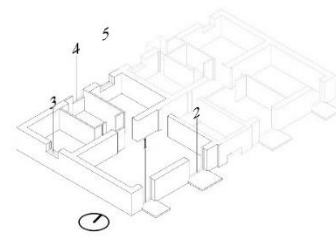
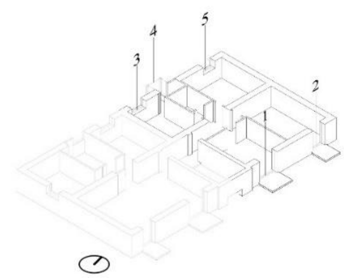
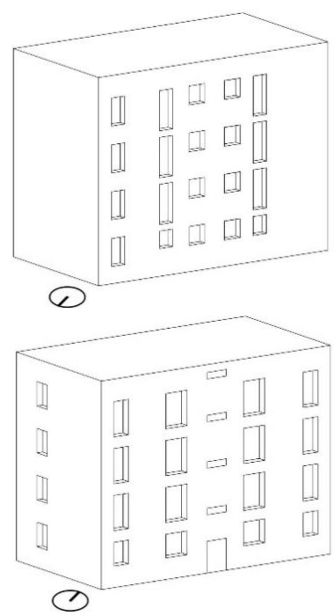
Apt 6 – second floor	1- PVC frame 2- PVC frame 3- PVC frame 4- aluminum frame 5- PVC frame	
Apt 7 – third floor	All PVC frames	
Apt 8 – third floor	1- PVC frame 2- PVC frame 3- PVC frame 4- aluminum frame 5- PVC frame	

Table 5 building's pre-renovation window details

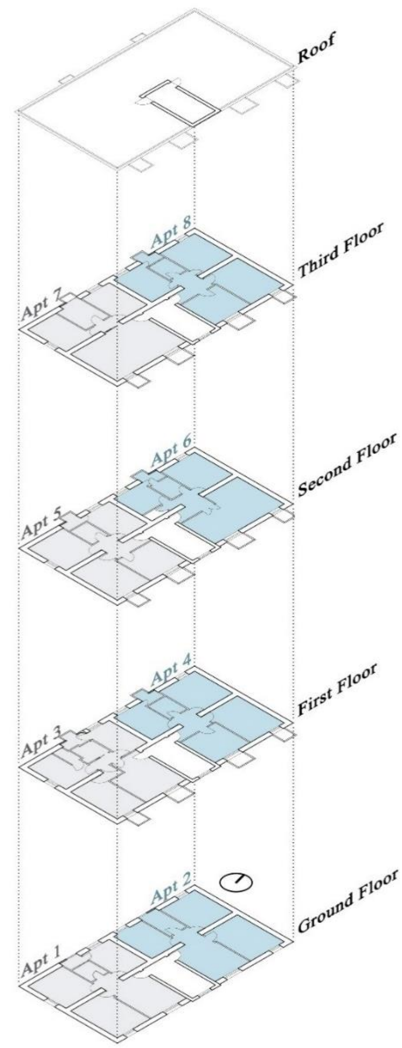
BUILDING GEOMETRY	
Net floor area (A)	498.8 m²
Volume (V)	2520 m³
Envelope area (S)	957.7 m²
Form factor (S/V)	0.38 m⁻¹
WWR	9.6%

Table 6 building's geometric data



APARTMENT AREAS		
Apt.	**Net floor area m²**	**Window area m²**
Apt 1	60.9	7.89
Apt 2	60	7.57
Apt 3	63.4	11.81
Apt 4	62.1	11.65
Apt 5	63.3	11.81
Apt 6	62.9	11.65
Apt 7	62.8	11.81
Apt 8	63.4	11.65

Table 7 apartment floor and window areas



3.2. Building VE model

The model's geometry is simplified in VE by avoiding elements unrelated to the energy analysis (e.g., nib walls, railings, etc.). Technical shafts are also avoided since they are not room bounding elements. In this chapter, the model inputs and results for the pre-renovation and post-renovation phases are provided. The final *inputs* used for the model are obtained after the *model verification*, which is explained in chapter 4. The following tables give detailed information about the different inputs related to the construction materials, user behaviors, internal gains, HVAC system.

3.2.1. Model inputs

CONSTRUCTION TEMPLATE	
Exterior wall - 40cm sandstone Layers (outside to inside): • Plaster (lightweight) 2cm • Sandstone 40cm • Plaster (lightweight) 2cm	U-value: 1.5748 W/m².K Total R-value: 0.4853 m²K/W
Interior partition - 10cm brick wall Layers (outside to inside): • Plaster (lightweight) 1.5cm • Brickwork (inner leaf) 10cm • Plaster (lightweight) 1.5cm	U-value: 1.6998 W/m².K Total R-value: 0.3488 m²K/W
Staircase wall - 25cm pietra cantone Layers (outside to inside): • Plaster (lightweight) 2cm • Sandstone 25cm • Plaster (lightweight) 2cm	U-value: 1.5709 W/m².K Total R-value: 0.3971 m²K/W
Internal ceiling/floor Layers (outside to inside): • Plaster (lightweight) 1cm • Reinforced concrete 16cm • Cast concrete (lightweight) 4cm • Tile bedding 1cm • Slate tiles 1cm	U-value: 2.1537 W/m².K Total R-value: 0.2495 m²K/W
Roof Layers (outside to inside): • felt/bitumen layers 0.5cm • Cast concrete (lightweight) 4cm • Reinforced concrete 16cm • Gypsum/plaster board 1.5cm	U-value: 2.4042 W/m².K Total R-value: 0.2786 m²K/W
Doors Plywood (lightweight): 5cm	U-value: 2.0703 W/m².K Total R-value: 0.3333 m²K/W

Table 8 construction materials data in VE (pre-renovation)

<table>
<tr><th colspan="4">WINDOW TEMPLATE</th></tr>
<tr><th>Apt.</th><th>Frame type</th><th>Frame materials (named according to VE)</th><th>Specification</th></tr>
<tr><td>1</td><td>All wood (x5)</td><td>Soft wood with double glazing of 6mm</td><td rowspan="8">Performance:
Net U-value (including frame): 3.0566 $W/m^2.K$
Net R value: 0.3340 m^2K/W
U-value (glass only): 2.9937 $W/m^2.K$
G-value (EN 410): 0.7072

Clear float 6mm:
Conductivity: 1.06 W/(m.K)
Transmittance: 0.78
Resistance: 0.0057 $m^2.K/W$

Cavity:
Resistance: 0.1730 $m^2.K/W$</td></tr>
<tr><td>2</td><td>All wood (x5)</td><td>Soft wood with double glazing of 6mm</td></tr>
<tr><td>3</td><td>All PVC (x7)</td><td>PVC with double glazing of 6mm</td></tr>
<tr><td>4</td><td>All PVC (x5)</td><td>PVC with double glazing of 6mm</td></tr>
<tr><td>5</td><td>PVC (x2)
Wood (x2)
Aluminum (x3)</td><td>All with double glazing of 6mm</td></tr>
<tr><td>6</td><td>PVC (x4)
Aluminum (x3)</td><td>PVC with double glazing of 6mm</td></tr>
<tr><td>7</td><td>All PVC (x5)</td><td>PVC with double glazing of 6mm</td></tr>
<tr><td>8</td><td>PVC (x4)
Aluminum (x3)</td><td>PVC with double glazing of 6mm</td></tr>
</table>

Table 9 window materials data in VE (pre-renovation)

HVAC		
Apt.	**Heating/cooling**	**DHW**
1	Electric heat pump	Electric heat pump
2	Electric heat pump	Electric heat pump
3	No installed system	No installed system
4	Electric heat pump	Electric heat pump
5	No installed system	No installed system
6	Electric heat pump	Gas-fired pump
7	Electric heat pump	Electric heat pump
8	Electric heat pump	Gas-fired pump

Table 10 HVAC systems of each apartment (pre-renovation)

USER BEHAVIOR		
Apt.	**Number of users – profession**	**Active hours**
1	1 – teacher	07:00-08:30 / 17:00-23:30
2	1 – (unknown)	10:00-23:00
3	3 – students	07:00-08:00 / 18:30-24:00
4	1 – police	06:00-07:30 / 18:00-23:30
5	1 – (unknown)	10:00-12:00 / 15:00-19:00 / 21:00-23:00
6	1 – engineer	07:00-08:30 / 18:30-23:30
7	4 – family	06:30-24:00
8	1 – old member	08:30-12:00 / 19:00-23:30

Table 11 apartment's user data

WEATHER DATA	
Weather file	User defined .epw file based on 2019 weather data
Latitude (°)	39.25
Longitude (°)	9.05
Elevation (m)	2

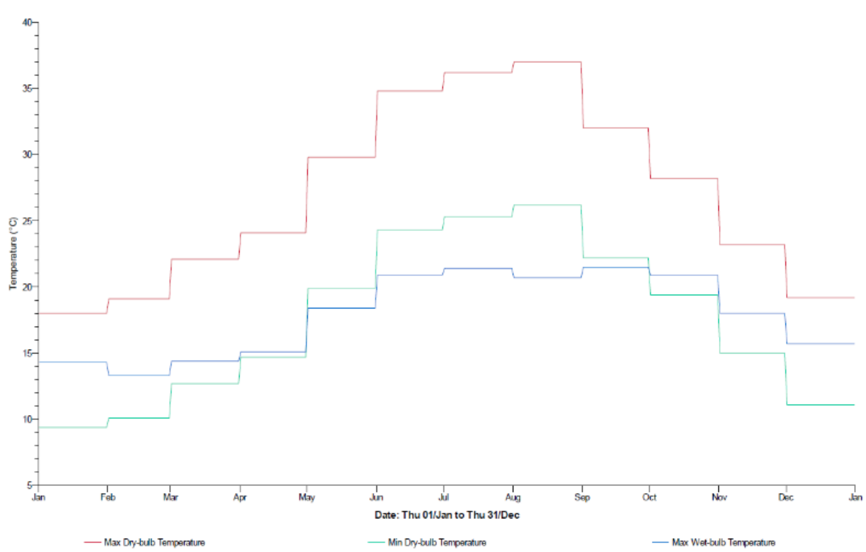


Table 12 temperature data (IES-VE)

INTERNAL GAINS | APARTMENTS			
Lighting	**Computers**	**People**	**Cooking**
Max. sens. gain: 2 W/m²	Max. sens. gain: 20 W	Max. sens. gain: 70 W/person Max. latent gain: 30 W/person	Max. sens. gain: 9 W/m²
INTERNAL GAINS | COMMON SPACE (STAIRCASE)			
Lighting			
Max. sensible gain: 2 W/m² Max. power consumption: 2 W/m²			

Table 13 internal gains (IES-VE)

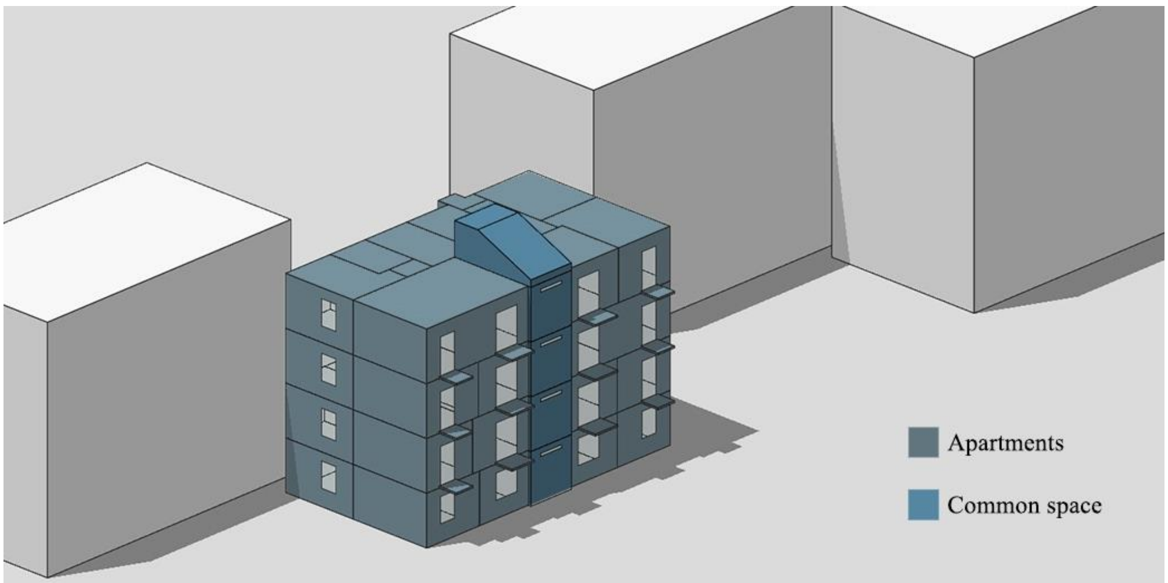


Figure 6 model viewer (IES-VE)

3.2.2. Results of the energy consumption before renovation work

Following the previously provided inputs, the simulation results obtained from the software are summarized in Figure 7**.** Apartment 7 shows the highest consumption during the whole year, which is explained with the number of users, occupation hours, and location (last floor, having poorly insulated roof). Apartments 3 and 5 show lower electricity consumption compared to the rest due to the absence of an HVAC system. Apartment 8 shows high consumption during the heating season, even though it has a single member and short occupation schedule, this is explained by its position: north-oriented and located on the last floor which is covered by a poorly insulated roof. The previously provided inputs and building data give important insight into the energy consumption profiles and the different variables that are affecting the consumption, which can be seen clearly from the final monthly results.

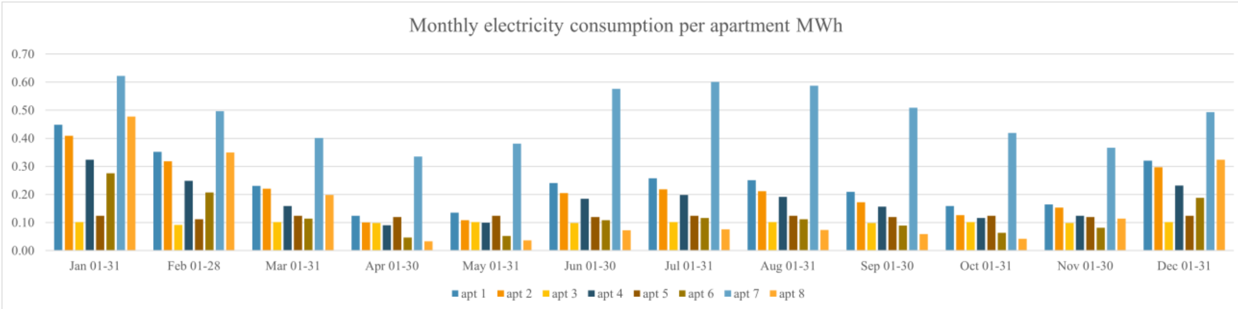
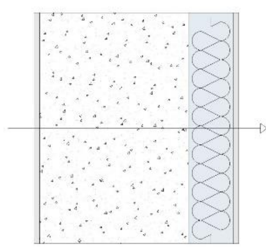
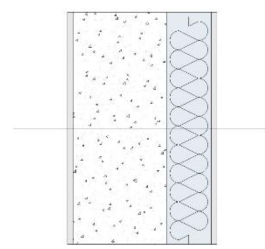
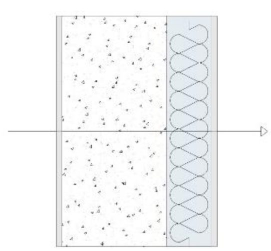
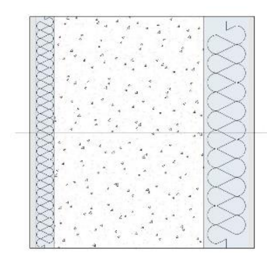


Figure 7 monthly electricity consumption per apartment (pre-renovation)

3.2.3. Retrofit intervention inputs

The building went through a renovation process during the implementation period of this work. The renovation is conducted by R2M, which provided the details of the performed work. The renovation includes providing a centralized HVAC system, the installation of a PV plant with a total installed power of 20 kWp, enhancing the thermal insulation for the vertical components and the roof. Below are the tables that provide in detail the specification of the renovated components and systems.

COMPONENT'S STRATIGRAPHY		
Exterior walls	**U-value:** 0.2520 W/m².K **Total R-value:** 3.7980 m²K/W  Layers (outside to inside): • 1.5 cm plaster • 12 cm insulation • 40 cm sandstone • 1.5 cm plaster	**U-value:** 0.2530 W/m².K **Total R-value:** 3.6922 m²K/W  Layers (outside to inside): • 1.5 cm plaster • 12 cm insulation • 22 cm sandstone • 1.5 cm plaster
	U-value: 0.2519 W/m².K **Total R-value:** 3.7098 m²K/W  Layers (outside to inside): • 1.5 cm plaster • 12 cm insulation • 25 cm sandstone • 1.5 cm plaster	**U-value:** 0.1867 W/m².K **Total R-value:** 5.1869 m²K/W  Layers (outside to inside): • 1.5 cm plaster • 12 cm insulation • 40 cm sandstone • 5 cm insulation • 1.5 cm plaster

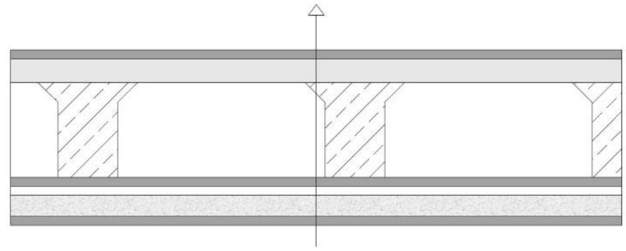
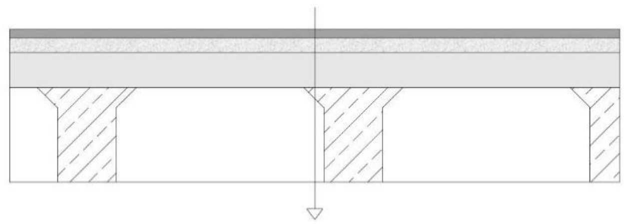
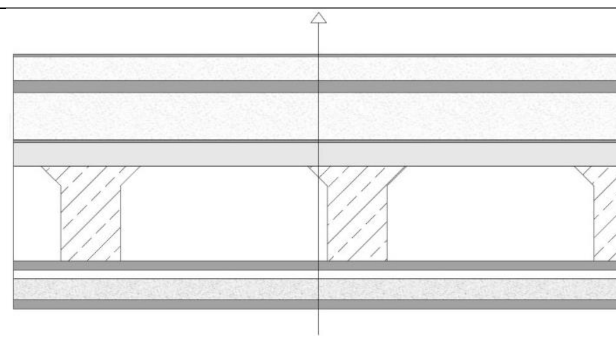
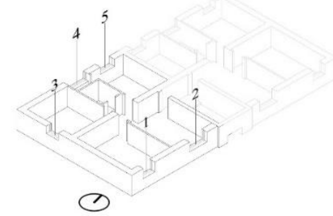
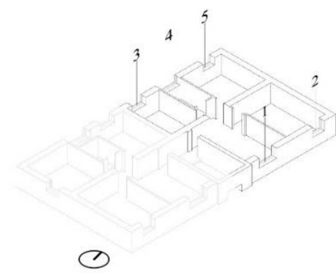
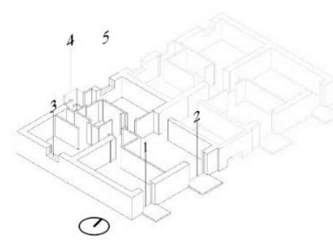
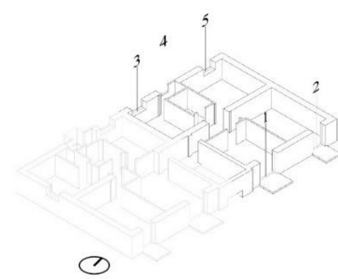
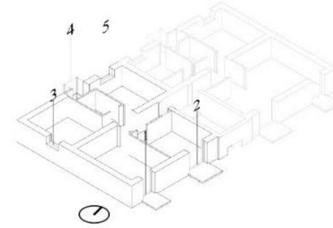
Internal ceiling /floor	**U-value:** 0.4992 W/m².K **Total R-value:** 1.8031 m²K/W Layers (outside to inside): • 1.5 cm ceramic tiles • 4 cm cement mortar layer • 16 cm RCC slab • 1.5 cm gypsum board • 1.5 cm non-ventilated air gap • 3.5 cm Radiant roof • 1.5 cm gypsum boar	 Internal horizontal partition with radiant ceiling
Internal ceiling /floor	**U-value:** 0.6462 W/m².K **Total R-value:** 1.2076 m²K/W Layers (outside to inside): • 16 cm RCC slab • 6 cm cement mortar layer • 2.4 cm radiant floor • 1.5 cm ceramic tiles	 Internal horizontal partition with radiant floor
Roof	**U-value:** 0.2763 W/m².K **Total R-value:** 3.4528 m²K/W Layers (outside to inside)*: • 0.4 cm rubber floor • 4 cm expanded polyurethane • 2 cm cement mortar layer • 8 cm perlite and vermiculite • 0.5 cm asphalt for waterproofing • 4 cm sand and gravel concrete • 16 cm RCC slab • 1.5 cm gypsum board • 1.5 cm non-ventilated air gap • 3.5 cm radiant ceiling • 1.5 cm gypsum board	 Roof top with radiant ceiling underneath

Table 14 building's post-renovation component stratigraphy (U-values and total R-values as given in VE)

*1.5 cm non-ventilated air gap is not inserted in VE model due to layer limit of 10.

WINDOWS		
Apt	**Frames**	**Axonometric floor plans**
Apt 1 – ground floor	All PVC frames U-values (W/m².K): 1- 1.25 2- 1.3 3- 1.25 4- 1.35 5- 1.35	
Apt 2 – ground floor	All PVC frames U-values (W/m².K): 1- 1.3 2- 1.25 3- 1.35 4- 1.35 5- 1.25	
Apt 3 – first floor	All PVC frames U-values (W/m².K): 1- 1.41 2- 1.36 3- 1.25 4- 1.33-1.51 5- 1.35	
Apt 4 – first floor	All PVC frames U-values (W/m².K): 1- 1.36 2- 1.41 3- 1.35 4- 1.495 5- 1.25	
Apt 5 – second floor	All PVC frames U-values (W/m².K): 1- 1.41 2- 1.36 3- 1.25 4- 1.32-1.5 5- 1.35	

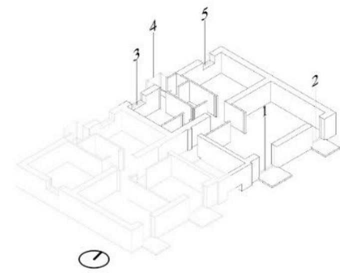
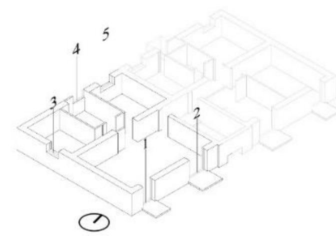
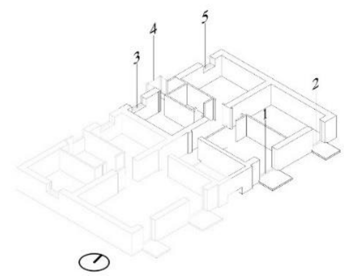
Apt 6 – second floor	All PVC frames 1- 1.36 2- 1.41 3- 1.35 4- 1.32-1.5 5- 1.25	
Apt 7 – third floor	All PVC frames U-values (W/m².K): 1- 1.41 2- 1.36 3- 1.25 4- 1.43 5- 1.35	
Apt 8 – third floor	All PVC frames U-values (W/m².K): 1- 1.36 2- 1.41 3- 1.35 4- 1.32-1.5 5- 1.25	

Table 15 building's post-renovation window material and U-values

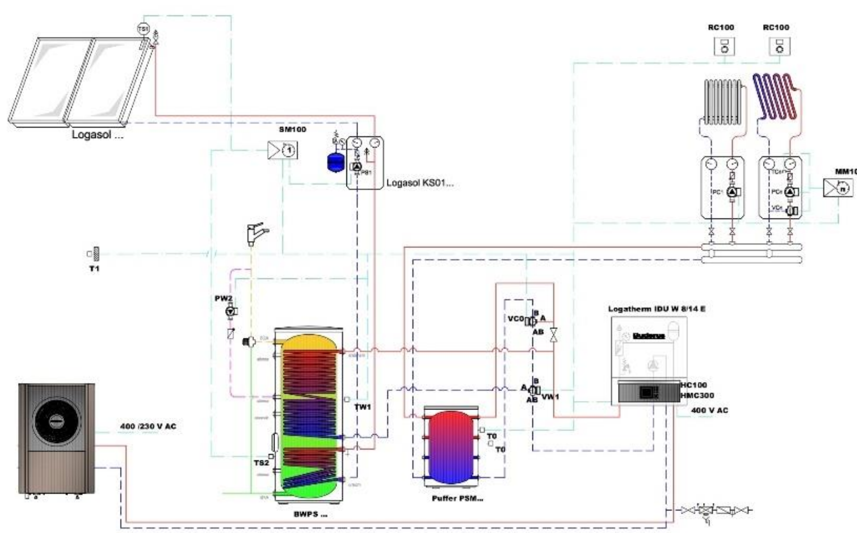


Figure 8 PI diagram

*The inputs and the PI diagram are provided by the project coordinator: R2M

3.2.4. Results of the new energy demand after renovation works

There are two different results obtained from the post-renovation model: 1- the actual energy consumption, 2- the energy demand. The former is obtained by inserting the real HVAC system specifications to compare the energy consumption before and after renovation, to see the impact it had on the building. The latter is the energy demand without the HVAC system, which will be designed in iVN as one of the EC members.

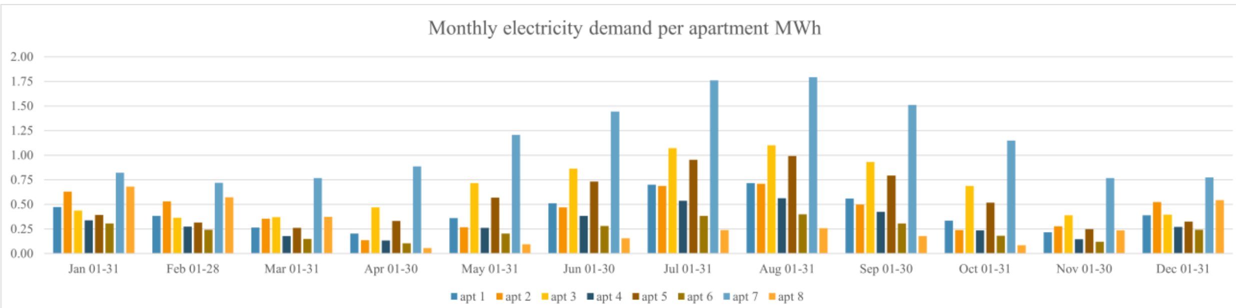


Figure 9 monthly electricity demand per apartment (post-renovation)

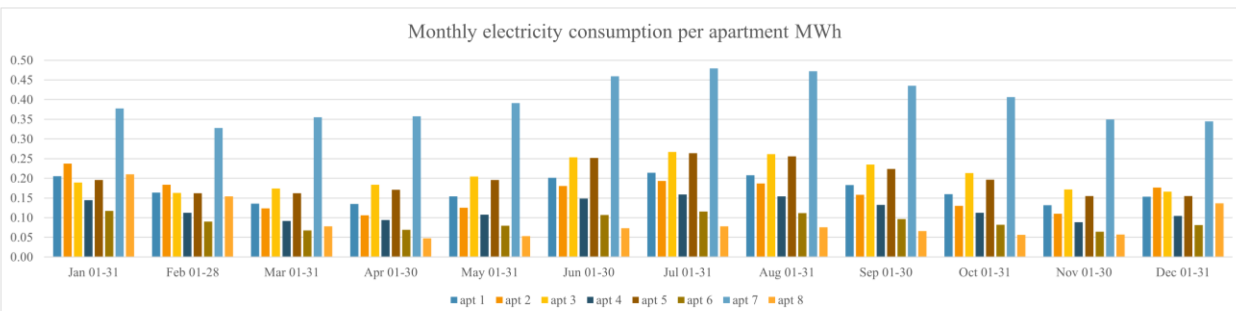


Figure 10 monthly electricity consumption per apartment (post-renovation)

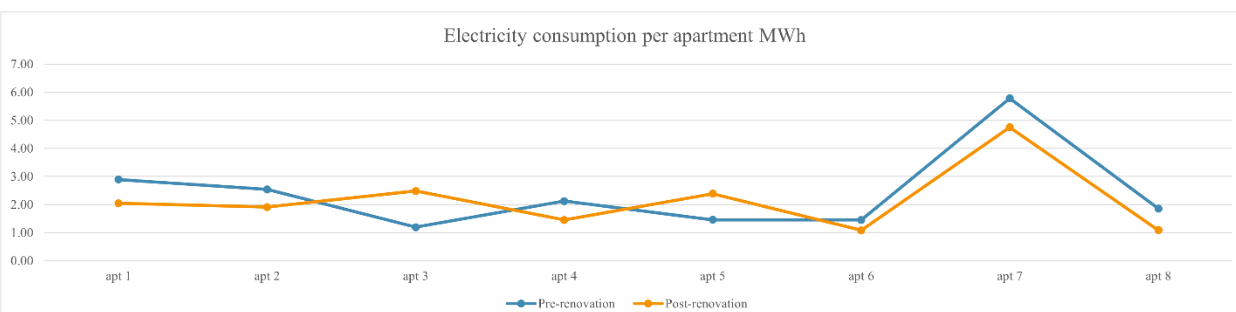


Figure 11 pre-renovation and post-renovation energy consumption comparison

The results illustrated in Figure 11 show a decrease of 29% for apartment 1, 25% apartment 2, 32% apartment 4, 26% apartment 6, 18% apartment 7, and 42% for apartment 8. Apartments 3 and 5 show higher results in the post-renovation case, which is explained by the lack of an HVAC system in the pre-renovation phase.

3.3. EC scenarios

3.3.1. Condominium scale

- 3.3.1.1. 1 POD

This scenario has a single POD where there is no energy shared and no EC incentive (Figure 12 a). The common uses include the HVAC system, solar water heating, and the common staircase area's electricity demand.

- 3.3.1.2. 2 PODs

In this scenario, the main POD (POD 1) is connected to the common uses, POD 2 is connected to the 8 apartments. In this case, there is a REC incentive for the energy shared with POD 2, which is not a direct share but incentivized by the government (Figure 12 b).

The aim of this scenario is to test the energetic, environmental, and economic performance of the building, analyzing the potential choice of aggregating the energy into one or two PODs. The scenario will also consider the installation of an electricity storage system (BT) for each case, which helps in improving the self-consumption levels of the community.

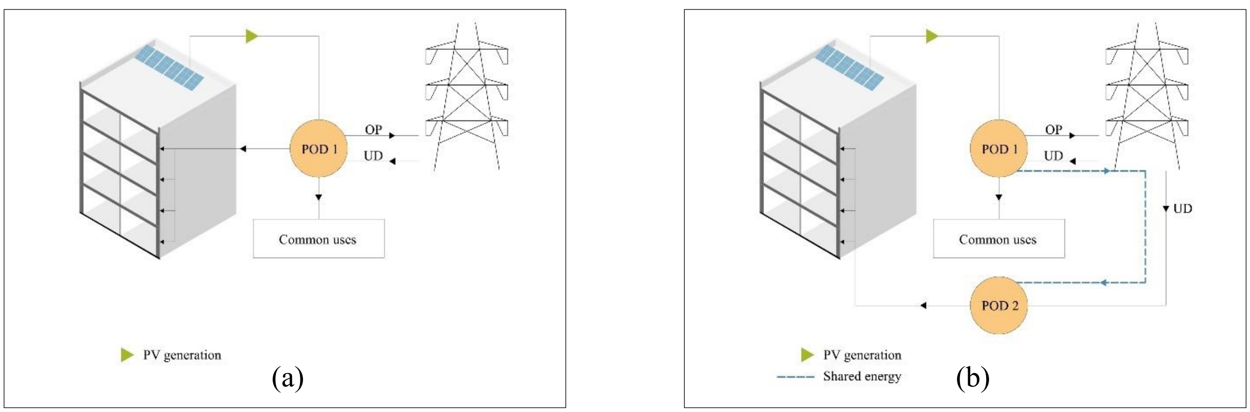


Figure 12 condominium scale scenario scheme

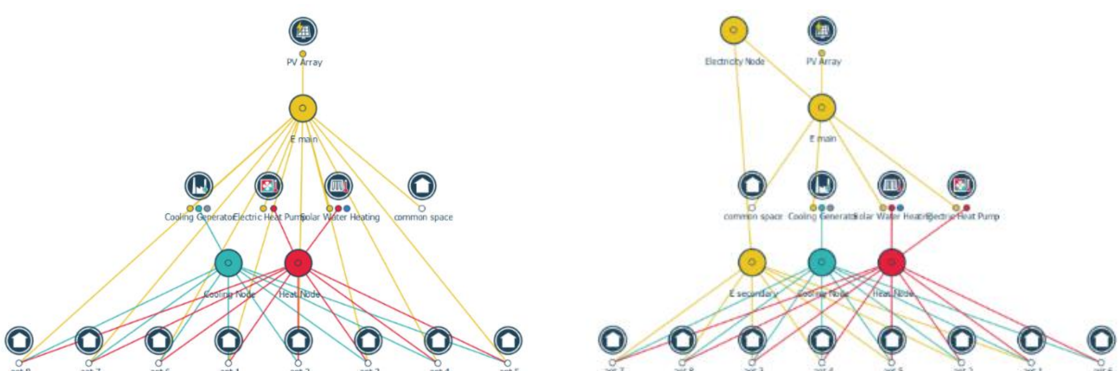


Figure 13 iVN view – Condominium scale scenario

The battery storage system will be installed to the main electricity node (E main) in both cases (Figure 13). Considering the current network, it is not possible to test batteries serving the apartments since the POD that aggregates the demand of the apartments (E secondary) is not connected to a generation source.

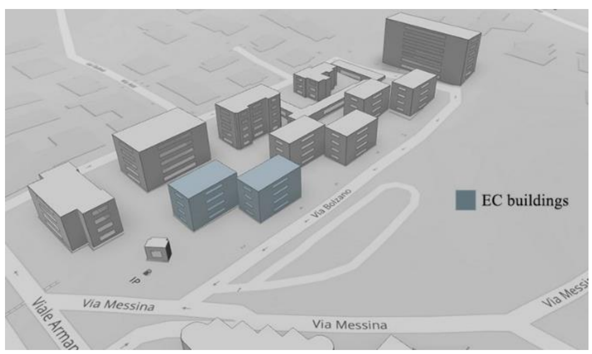
3.3.2. EC with a neighboring building

The aim of this scenario is to understand the shareable energy in which the main analyzed condominium can share with a neighboring building. The scenario will test different cases to demonstrate the economic, energetic, and environmental effects of the retrofit improvements.

3.3.2.1. Case A: 2 non renovated buildings

3.3.2.2. Case B: 2 renovated buildings

- B+BT20: using a battery with 20 kWh capacity
- B+BT40: using a battery with 40 kWh capacity
- B+BT60: using a battery with 60 kWh capacity



(Case A-B)

Figure 14 iVN 3D model view – EC with a neighboring building

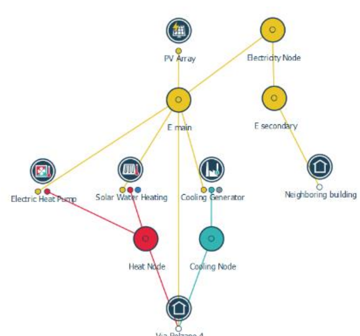


Figure 15 iVN view – EC with a neighboring building

The energy prices and investment cost that are used for the economic calculations are given below:

Energy prices for residential sector	
Withdrawal from grid	**0.22 €/kWh**
REC incentive	**0.10956 €/kWh**
Feed-in tariff	**Table 17-18**
Investment costs*	
PV	**1600 €/kWp**
Battery	**500 €/kWh**
Battery replacement cost	**250 €/kWh**
Battery lifetime	**10 years**

Table 17 Energy prices and investment costs used for the scenarios

(Todeschi et al., 2021, p.3)

Energy feed-in tariff in Sardinia according to different months (€/MWh)						
	Jan	**Feb**	**Mar**	**Apr**	**May**	**Jun**
F1	48.77	63.33	56.59	50.87	55.47	58.15
F2	48.06	54.05	50.96	45.13	51.26	49
F3	44.43	45.83	42.62	32.17	39.56	48.58
	Jul	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
F1	63.79	67.9	67.9	69.1	70.49	68.57
F2	58.42	63.38	63.38	69.32	65.08	64.48
F3	50.54	58.61	58.61	63.3	60.45	57.59

Table 18 Energy feed-in tariff in Sardinia, GSE 2018

<table>
<tr><th colspan="25">Energy feed-in tariff in Sardinia according to different hours</th></tr>
<tr><th></th><th>0</th><th>1</th><th>2</th><th>3</th><th>4</th><th>5</th><th>6</th><th>7</th><th>8</th><th>9</th><th>10</th><th>11</th><th>12</th><th>13</th><th>14</th><th>15</th><th>16</th><th>17</th><th>18</th><th>19</th><th>20</th><th>21</th><th>22</th><th>23</th></tr>
<tr><th>Mon-Fri</th><td colspan="7">F3</td><td>F2</td><td colspan="11">F1</td><td colspan="4">F2</td><td>F3</td></tr>
<tr><th>Sat</th><td colspan="7">F3</td><td colspan="16">F2</td><td>F3</td></tr>
<tr><th>Sun</th><td colspan="24">F3</td></tr>
</table>

Table 16 Hourly feed-in tariff according to time and weekday, GSE 2018

4. Model verification

4.1. Energy performance gap

It is essential to validate the simulated model with the actual data to minimize the EPG that may occur later between the intended design and the real one.

The reliability of the design phase is associated with having detailed inputs about people's behavior, the used HVAC system, the correct weather file, internal gains, construction materials, etc. Following these requirements, it is quite challenging to acquire a perfect matching model when not all the inputs are available. For this aspect, several simulation trials are tested to understand the most influential inputs that cause a significant difference between the obtained results and the available data from the bills. The results show that people's behavior is the most critical input that has a considerable change in the obtained results. Also, the behavior of people regarding window openings is very important, which in long term is reflected in the electricity consumption for space heating and cooling. Another aspect is to assign realistic heating and cooling system control switches. The effort taken to minimize the EPG in this model includes: 1- following the heating system control switch for Cagliari: 15 November/31 March (10hrs/day), 2- creating a user-defined weather file, referenced to the year in which the available electricity bills are related to, 3- understanding how the user behavior affect the results and following occupancy schedule in compliance with the user profession, 4- using the provided appliance specifications and referring to standard values in case of absent input data.

The following figure shows the different energy consumption results when changing the DHW system inputs and the consumption amount per user:

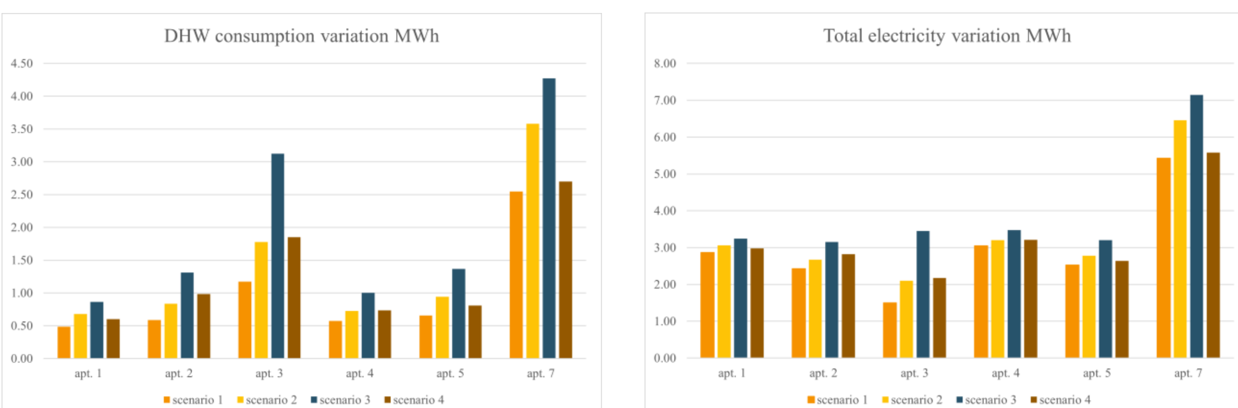


Figure 16 yearly apartments consumption related to different DHW scenarios

SCENARIO 1				SCENARIO 2		
Apt.	**Consumption l/(h.person)**	**Storage volume (l)**	**Hot water temperature (°C)**	**Consumption l/(h.person)**	**Storage volume (l)**	**Hot water temperature (°C)**
1	1.5	50	42	1.5	50	50
2	1.3	80	40	1.3	80	50
3	1	35	42	1	35	50
4	1.1	80	45	1.1	80	50
5	1.5	35	43	1.5	35	50
7	1.5	50	45	1.5	50	50
SCENARIO 3				**SCENARIO 4**		
Apt.	**Consumption l/(h.person)**	**Storage volume (l)**	**Hot water temperature (°C)**	**Consumption l/(h.person)**	**Storage volume (l)**	**Hot water temperature (°C)**
1	2	50	50	2	50	42
2	2.3	80	50	2.3	80	45
3	1.8	35	50	1.8	35	39
4	1.7	80	50	1.7	80	43
5	2.25	35	50	2.25	35	38
7	1.8	50	50	1.8	50	41

Table 19 four different scenarios for DHW pump inputs that affect the total consumption of the apartments

*Apt 6 and 8 are not considered in this comparison since they have gas-fired pumps for DHW

The following graph shows the different energy consumption results when changing the user behaviors of each apartment:

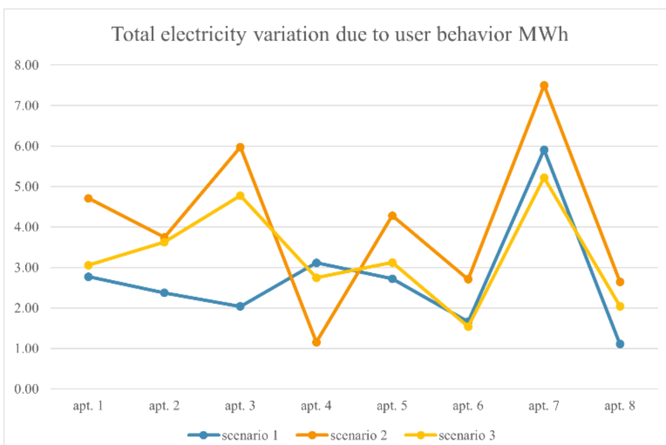


Figure 17 Electricity consumption variations related to different user behavior scenarios

The results shown above are related to two different variables associated with user behaviors that considerably affect the simulation results. Still, for the validation of a whole building, the various inputs of every apartment are crucial due to the interaction between the adjacent apartments through conduction gains, which means that the incorrect results of a single apartment will also affect the other ones.

The efforts to get the closest results are associated with using the nearest weather data file and reasonably changing the inputs of user behavior. The following part will discuss the methodology followed in this regard for validating the model.

4.2. Energy audit

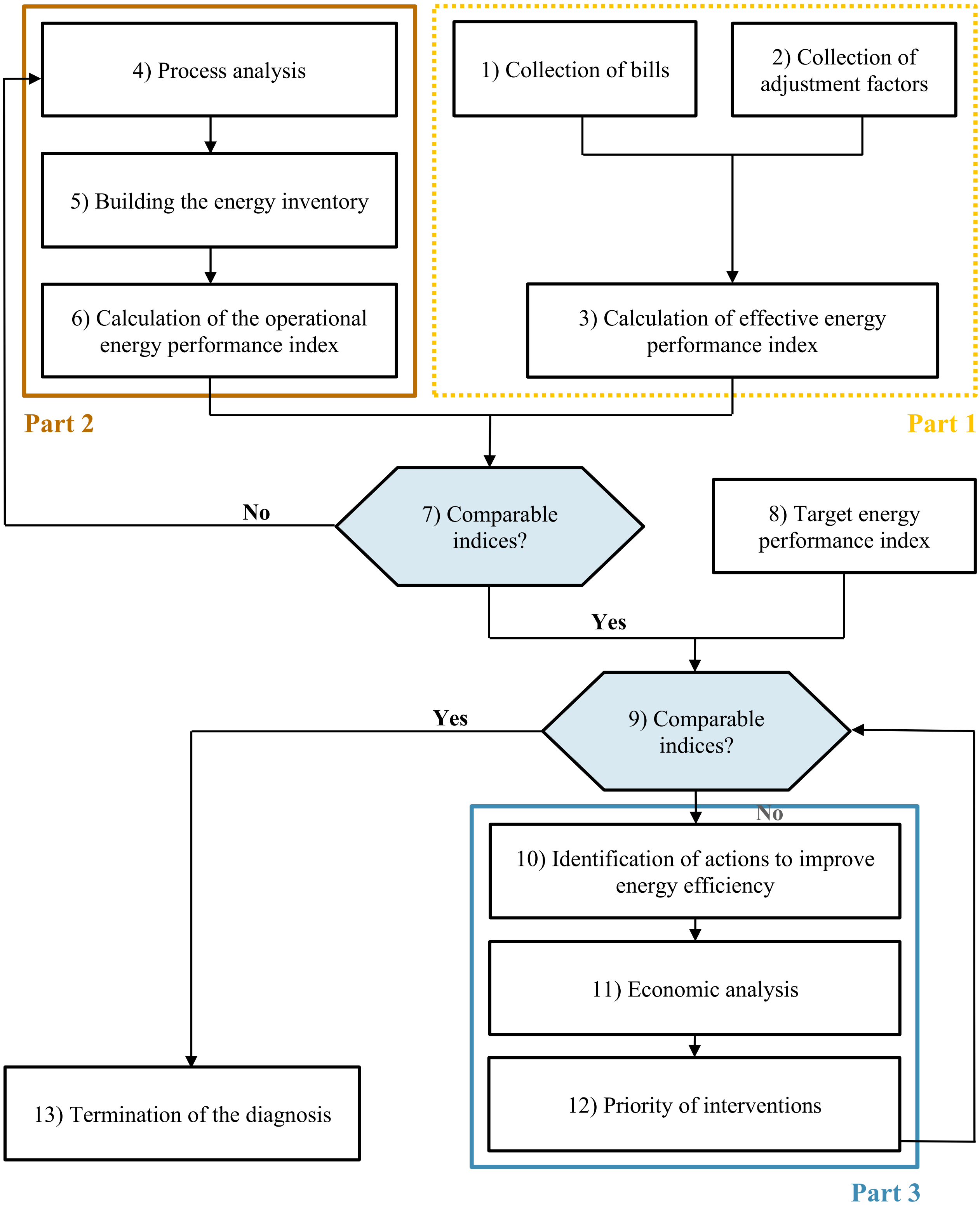


Figure 18 energy analysis scheme, based on UNI CEI EN 16247-2:2014

The methodology followed for the model validation is the energy audit described in the European standard UNI CEI EN 16247-2:2014

Figure 18 shows the flowchart of the process. The flow is divided into three main parts better to describe the general flow of the whole work:

1. **Part 1:** Data collection about the building:
   Electricity bills, construction materials, number of users, used appliances.
2. **Part 2:** Modeling the building:
   Inserting the provided data in part 1, checking the results of simulations, working on adjustments to validate the model.
3. **Part 3:** intervention scenarios:
   Testing scenario results and analyzing their economic, energetic, and environmental results to define the most efficient interventions.

The input details of the analyzed building, provided in chapter 3.2.1, are inserted into the model, and the first simulation results are obtained. *(Part 1 of the energy audit)*. Due to the used old weather file and the uncertainty of the user behavior, the first results were not close enough to validate the model, so adjustments were made to obtain the closest results with the provided bills. Figure 19 shows the steps followed in the adjustment of the inserted inputs. *(Part 2 of the energy audit)*

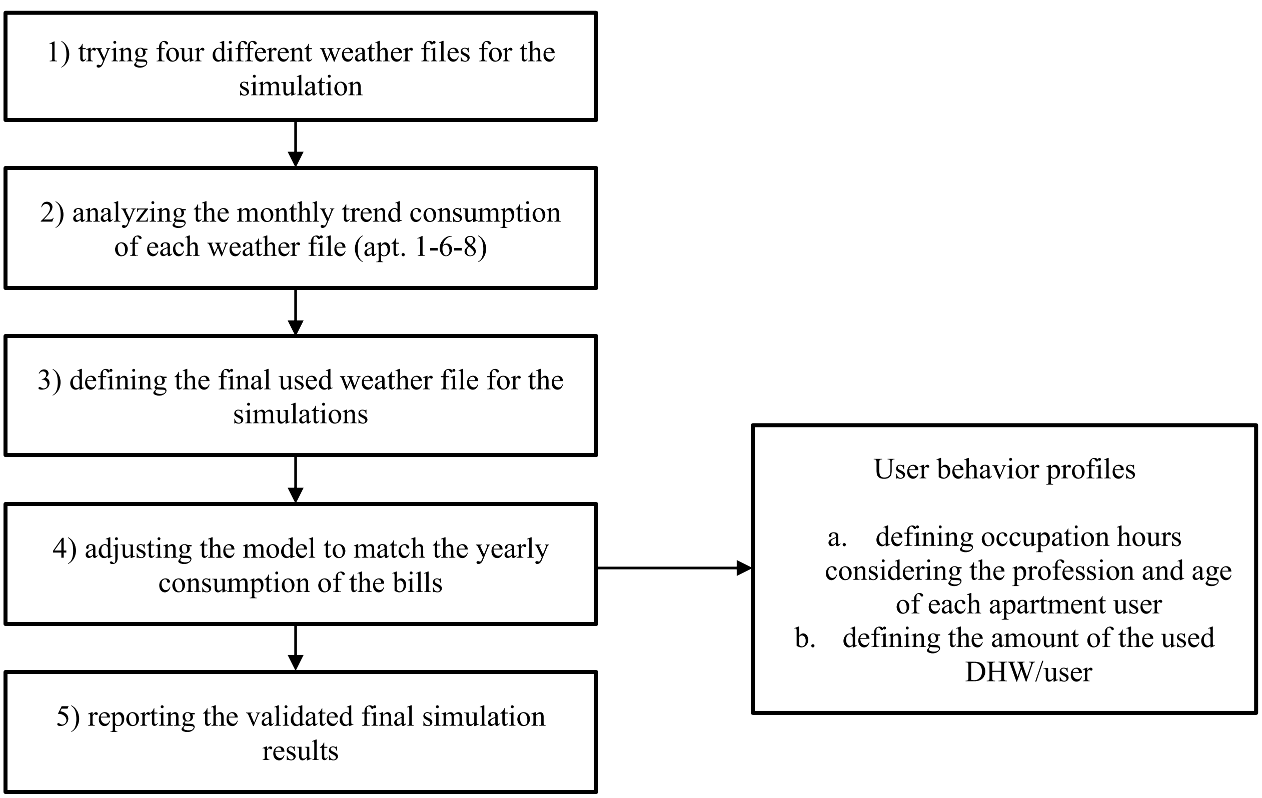


Figure 19 model adjustment

1) Trying four different weather data for the simulation

The graphs below show the data of the four weather files used for consumption comparison.

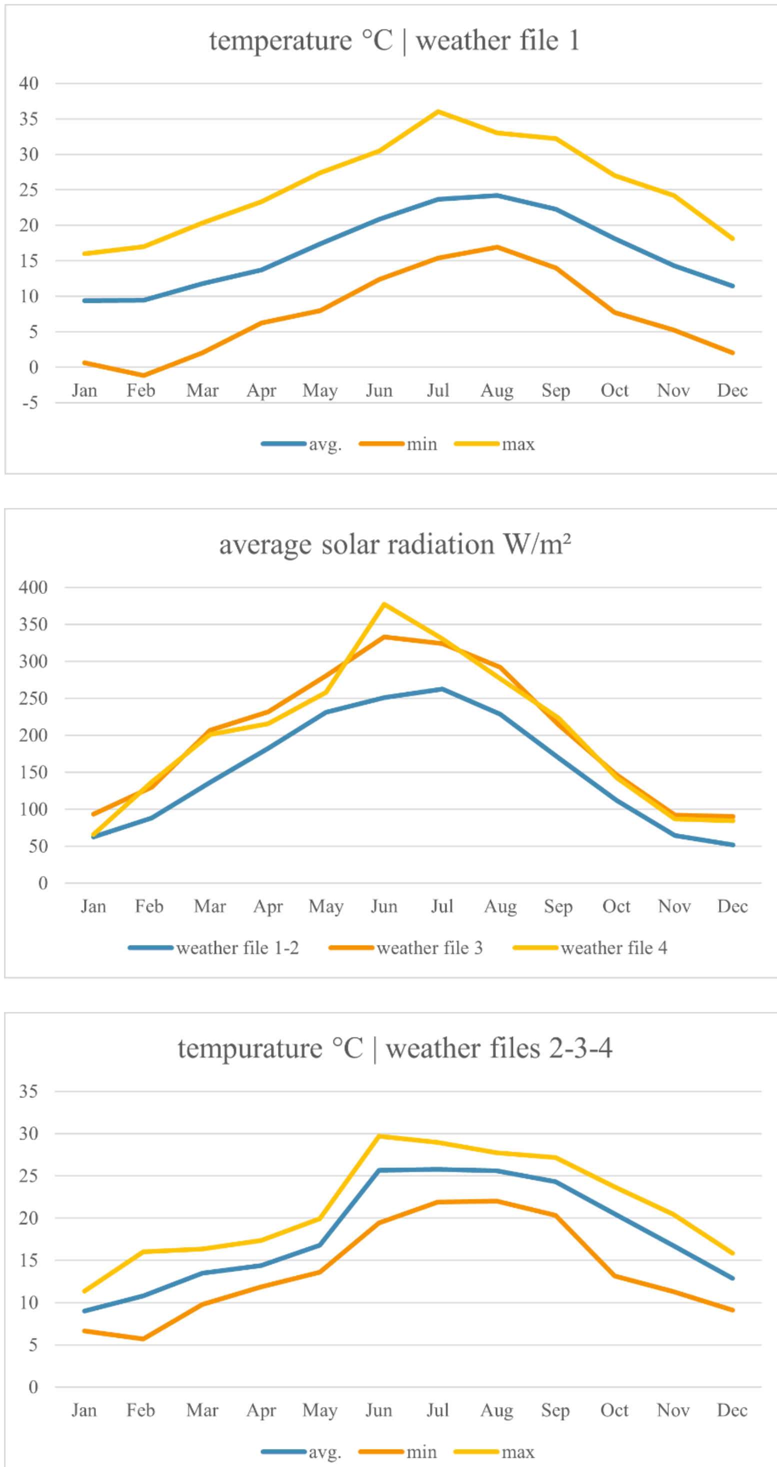
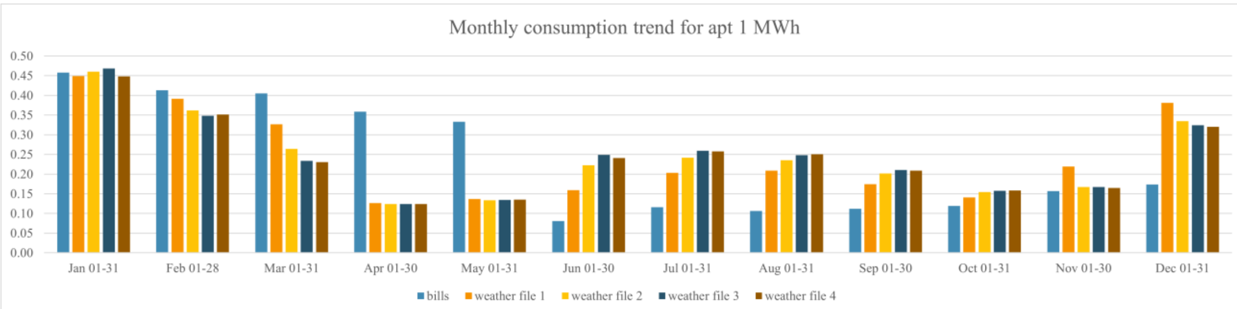


Figure 20 weather files tried for model verification

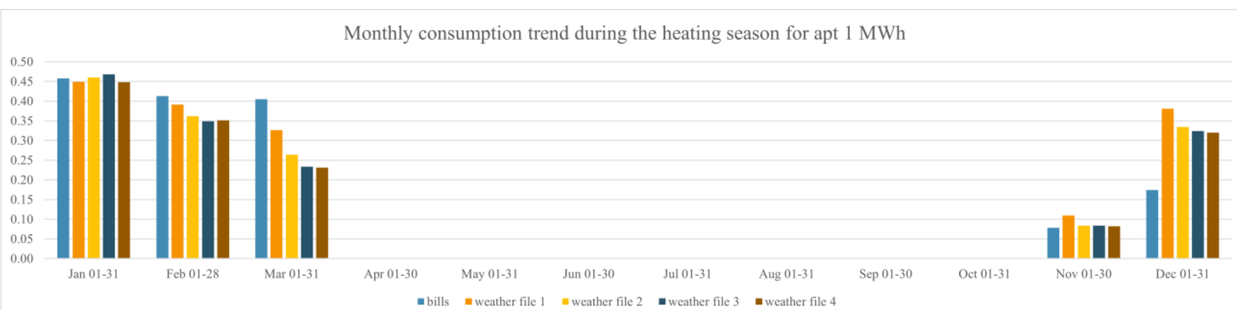
2) Analyzing the monthly trend consumption of each weather file (apt. 1-6-8)

The charts below illustrate the monthly consumption of three apartments for a whole year, considering the heating and cooling seasons separately too.

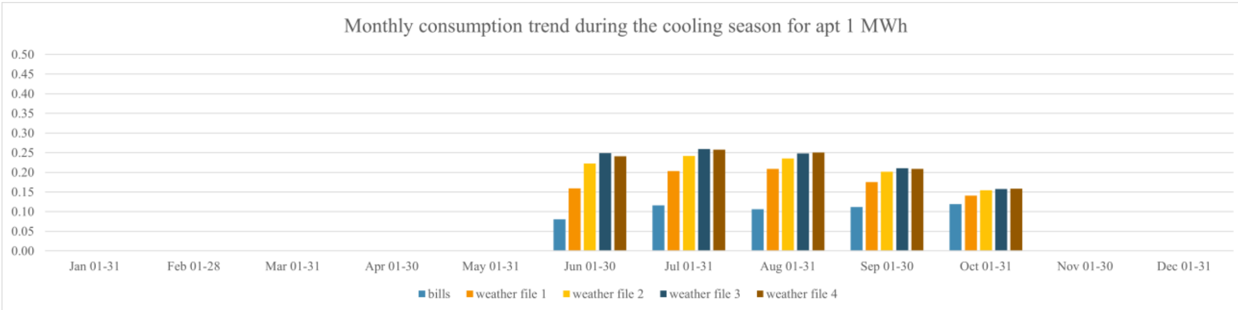
Apt. 1



Apt. 1 | yearly total consumption				
Weather file 1	Weather file 2	Weather file 3	Weather file 4	Available bills
2.917	2.901	2.924	2.892	2.833
103%	102%	103%	102%	

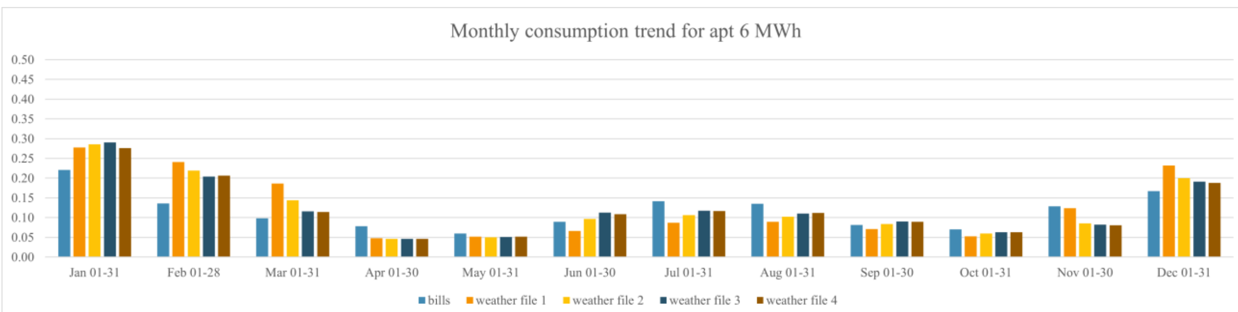


Apt. 1 | monthly winter consumption				
Weather file 1	Weather file 2	Weather file 3	Weather file 4	Available bills
1.657	1.504	1.458	1.433	1.529
108%	98%	95%	94%	

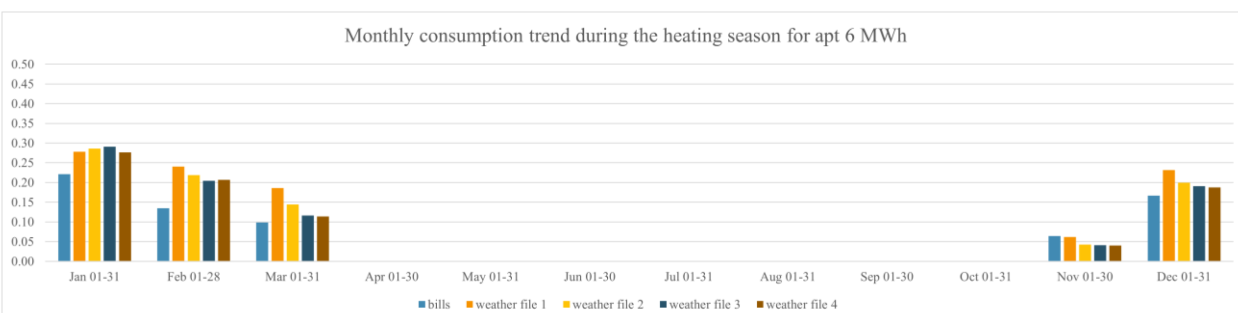


Apt. 1 | monthly summer consumption				
Weather file 1	Weather file 2	Weather file 3	Weather file 4	Available bills
0.887	1.055	1.124	1.117	0.534
166%	198%	211%	209%	

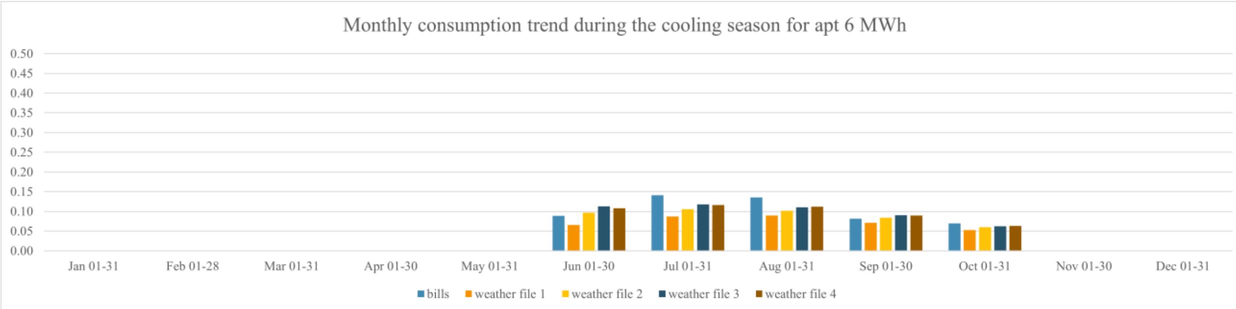
Apt. 6



Apt. 6 | yearly total consumption				
Weather file 1	Weather file 2	Weather file 3	Weather file 4	Available bills
1.527	1.479	1.476	1.453	1.407
109%	105%	105%	103%	

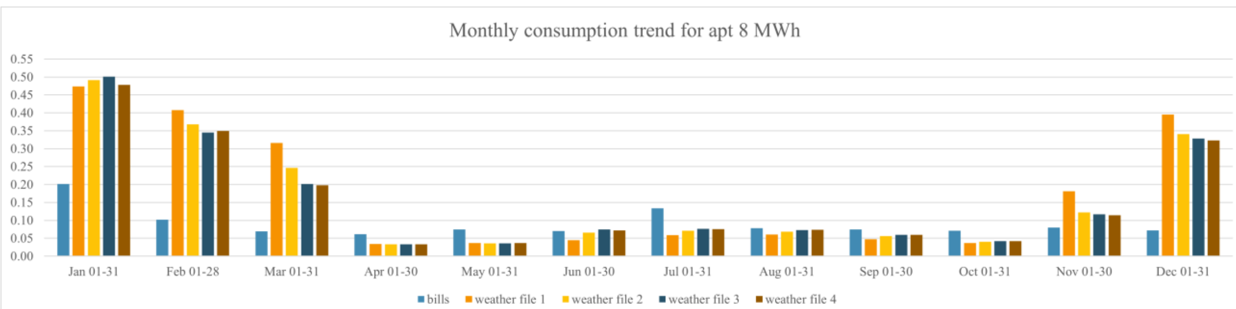


Apt. 6 | monthly winter consumption				
Weather file 1	Weather file 2	Weather file 3	Weather file 4	Available bills
0.998	0.891	0.843	0.825	0.687
145%	130%	123%	120%	

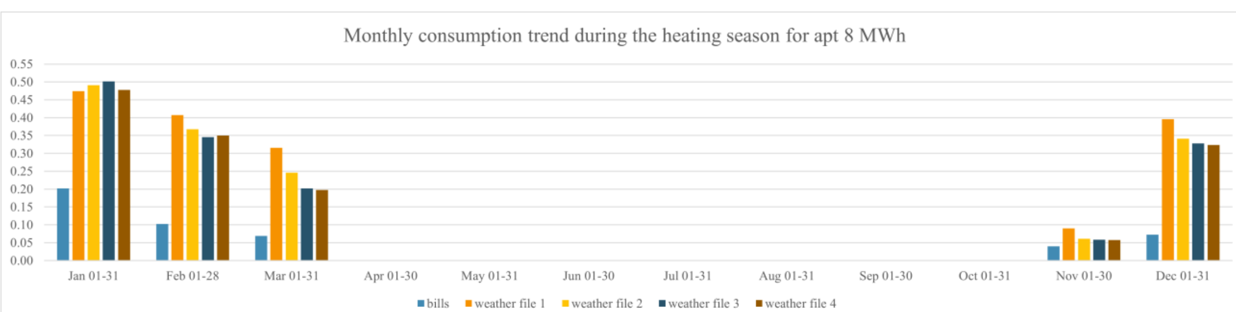


Apt. 6 | monthly summer consumption				
Weather file 1	Weather file 2	Weather file 3	Weather file 4	Available bills
0.367	0.449	0.493	0.489	0.517
71%	87%	95%	95%	

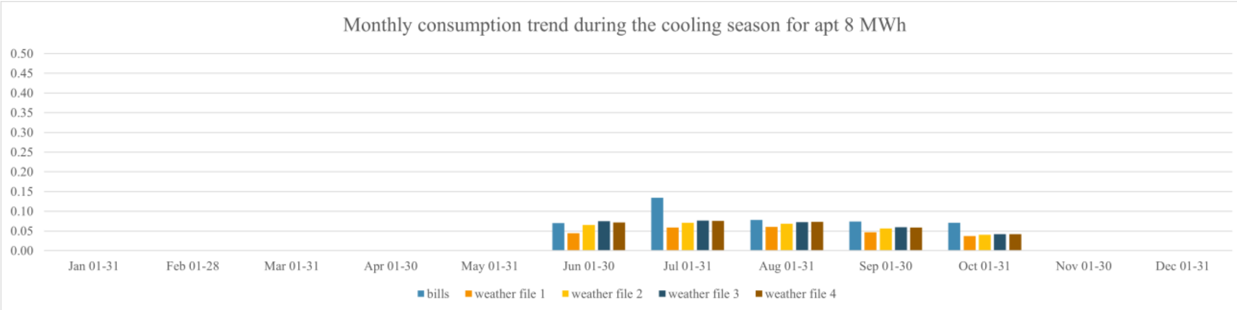
Apt. 8



Apt. 8 | yearly total consumption				
Weather file 1	Weather file 2	Weather file 3	Weather file 4	Available bills
2.093	1.938	1.888	1.856	1.088
192%	178%	174%	171%	



Apt. 8 | monthly winter consumption				
Weather file 1	Weather file 2	Weather file 3	Weather file 4	Available bills
1.683	1.507	1.435	1.405	0.485
347%	311%	296%	290%	



Apt. 8 | monthly summer consumption				
Weather file 1	Weather file 2	Weather file 3	Weather file 4	Available bills
0.249	0.302	0.326	0.323	0.427
58%	71%	76%	76%	

3) Defining the final used weather file for the simulations

Considering the results obtained from the four different weather files, weather file 4 showed the most relevant results when comparing both the monthly and yearly consumption trends of the analyzed apartments. The table below concludes the closest result obtained in each weather file when comparing yearly, summer, and winter consumptions of the analyzed three apartments (in which the monthly consumption from the bills is available).

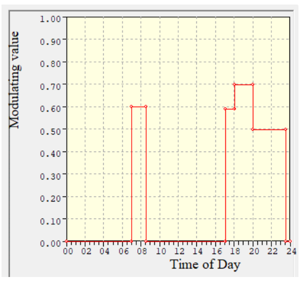
Weather files resolution				
	1	2	3	4
apt 1 total		x		x
apt 6 total				x
apt 8 total				x
apt 1 winter		x		
apt 6 winter				x
apt 8 winter				x
apt 1 summer	x			
apt 6 summer			x	x
apt 8 summer			x	x

In this verification, the aim was to use the correct weather file for the year in which the bills are provided (2019). The default TMY weather files are related to a long period of data collected from several years, which makes the comparison and model verification unreliable when verifying the simulation results with bills related to 2019.

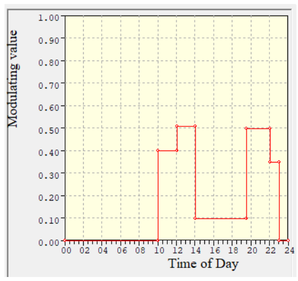
4) Adjusting the model to match the yearly consumption of the bills

a. Defining occupation hours considering the profession and age of each apartment user

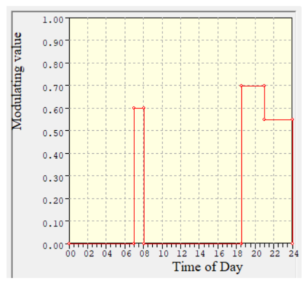
The trials made to define the most appropriate user behavior profiles are provided in chapter 4.1. Below are the definitive user behavior profiles of each apartment that resulted in the closest total yearly consumption. The modulating value defines the consumption density (coefficient). Values higher than 0.5 will trigger the cooling system to be switched on.



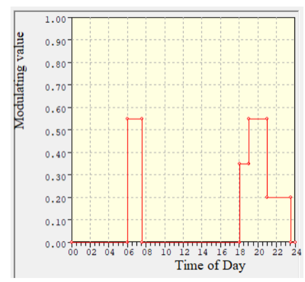
Apt. 1 - single teacher



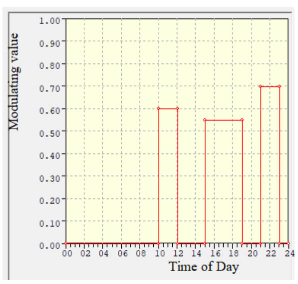
Apt. 2 - single user



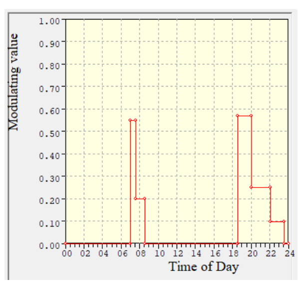
Apt. 3 - three users



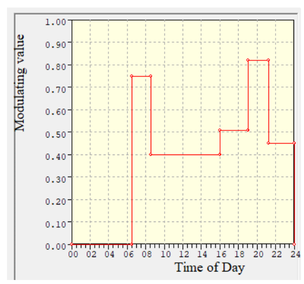
Apt. 4 – single policeman



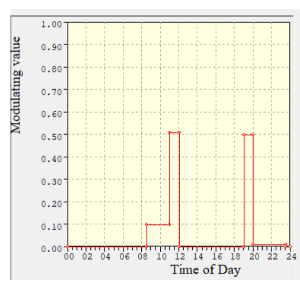
Apt. 5 – single user



Apt. 6 – single engineer



Apt. 7 – family of 4 members



Apt. 8 - single old user

Figure 21 daily user profiles for each apartment

b. Defining the amount of the used DHW/apartment

The trials made to define the most appropriate DHW consumption are provided in chapter 4.1. Below are the definitive DHW inputs of each apartment that resulted in the closest total yearly consumption:

Apt.	**Consumption l/(h.person)**
1	1.1
2	1.1
3	1.5
4	1.3
5	2.0
6	1.9
7	1.8
8	1.2

5) Reporting the validated final simulation results

Below are the final results obtained from the simulation with the previously provided inputs of:

- Weather file
- User-behavior
- DHW consumption

Date	apt 1	apt 2	apt 3	apt 4	apt 5	apt 6	apt 7	apt 8
Jan 01-31	0.448	0.409	0.102	0.324	0.124	0.276	0.622	0.478
Feb 01-28	0.351	0.318	0.092	0.249	0.112	0.207	0.496	0.350
Mar 01-31	0.231	0.221	0.102	0.159	0.124	0.114	0.401	0.198
Apr 01-30	0.124	0.101	0.098	0.090	0.120	0.047	0.335	0.033
May 01-31	0.135	0.108	0.102	0.099	0.124	0.052	0.381	0.037
Jun 01-30	0.241	0.205	0.098	0.185	0.120	0.108	0.576	0.072
Jul 01-31	0.258	0.218	0.102	0.198	0.124	0.116	0.600	0.076
Aug 01-31	0.251	0.212	0.102	0.192	0.124	0.112	0.587	0.074
Sep 01-30	0.209	0.172	0.098	0.156	0.120	0.089	0.509	0.059
Oct 01-31	0.159	0.127	0.102	0.116	0.124	0.063	0.419	0.042
Nov 01-30	0.165	0.153	0.098	0.124	0.120	0.081	0.367	0.114
Dec 01-31	0.320	0.297	0.102	0.232	0.124	0.188	0.493	0.323
Summed total	**2.892**	**2.540**	**1.196**	**2.123**	**1.456**	**1.453**	**5.785**	**1.856**
Available bills	**2.833**	**-**	**-**	**-**	**-**	**1.407**	**5.920**	**1.088**
	102%	-	-	-	-	**103%**	**98%**	**171%**

Table 20 final simulation results used for the base model verification (pre-renovation)

The simulation results obtained (Table 20) are close to the total yearly consumption of the three apartments with available bills (apt. 1-6-7). They are also close to the average consumptions in Sardinia*, which are: 2659.7 kWh/inhabitant/year (2018) and 5940.3/family/year (2017). However, apartment 8 shows higher consumption in the simulated model compared to the bills, which is explained by the lack of user behavior info. Another aspect that affects this result is the heating and cooling control switches, which are set in the model according to the control profile in Cagliari. But this input is not necessarily followed by the household, and together with the lack of user behavior info, the acquired result is accepted as verified following the validation of the other three apartments.

*tuttiitalia.it

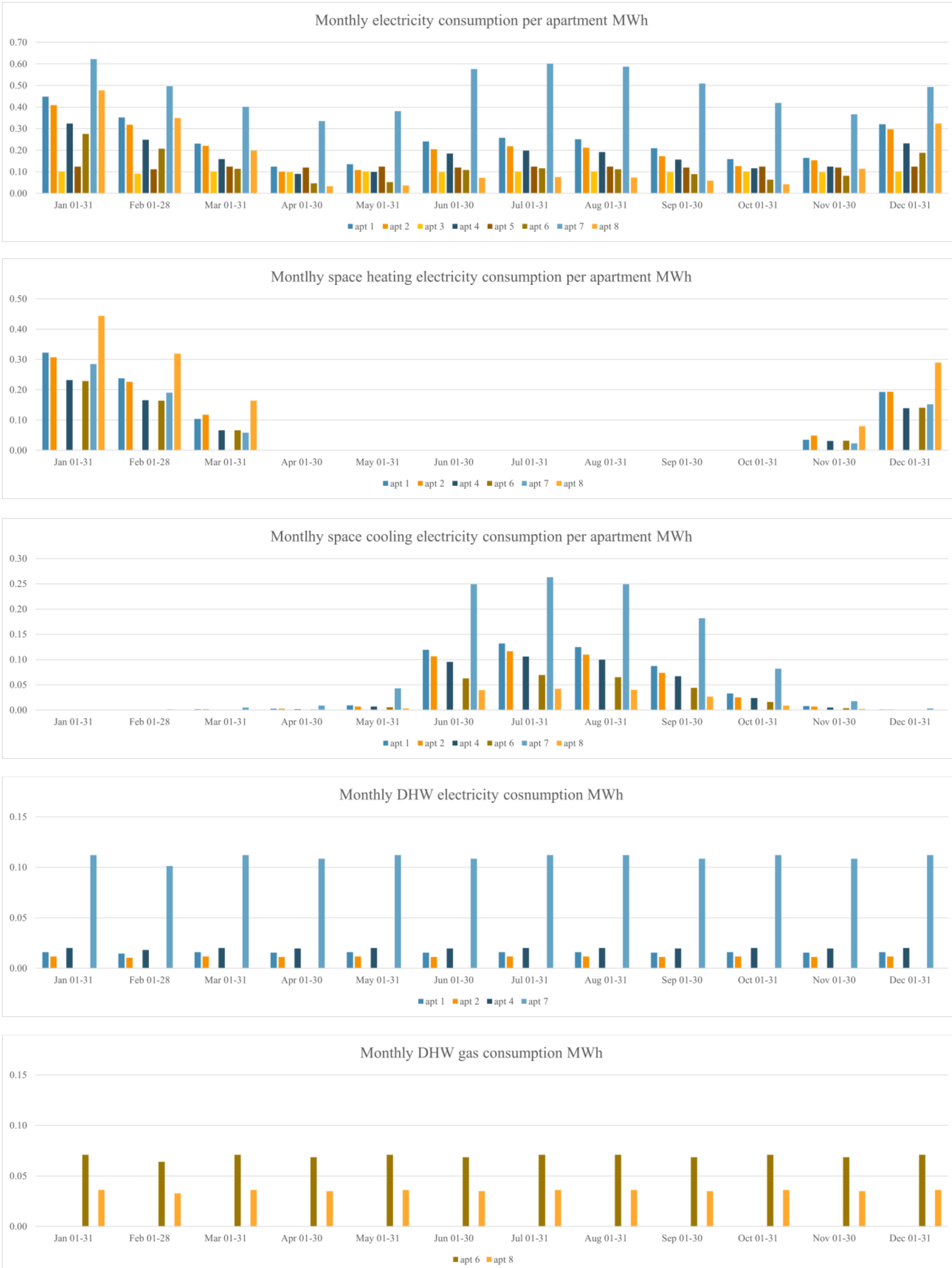


Figure 22 final verified consumption results for pre-renovation model

The consumption results illustrated in Figure 22 show a reasonable trend when comparing them with the input data of each apartment. Apartments 3 and 5 show low electricity consumption compared to the rest, due to the absence of an HVAC system. Apartments 6 and 8 show lower consumption compared to the other apartments with HVAC systems, since they use gas-fired heat pumps for DHW. The high consumption of apartment 7 in DHW is associated with the number of users (4). The space heating electricity consumption is high for apartments 7 and 8 which is explained by their position being on the last floor covered by a poorly insulated roof. Overall, apartment 7 has the highest consumption, which is associated with the number of users, position, and occupation hours.

Considering all these interpretations, the final obtained results show reasonable consumption trends for each apartment, which contributes to verifying the model.

5. Results and discussion

The scenarios are analyzed considering:

1. Energy performance indicators: *[56]*
   - SCI (self-consumption index): the share of locally self-consumed energy out of the total energy production by RES.
   - SSI (self-sufficiency index): the share of locally self-consumed energy out of the total energy consumption.

   SCI= (SC+CSC)/TP

   SSI= (SC+CSC)/TC

   where:

   SC: instantly self-consumed energy

   CSC: the share of energy that is exchanged among the REC members, which is the minimum between energy feed into the grid (OP) and the minimum between energy withdrawn from the grid (UD) by all REC members in each hourly period, min (OP:UD).

   TP: total production from RES

   TC: total consumption

2. Economic benefits: the Net Present Value (NPV) is calculated for each simulated scenario. The aim of using NPV is to determine the profitability of the analyzed case, considering the time value of money. It includes calculating the positive cash flows (benefits) and negative cash flows (costs) in each period of the investment. A positive NPV results in profit, while a negative NPV results in a loss.

   $$NPV = \sum_{t=0}^{N} \frac{R_t}{(1+r)^t}$$

   where:

   R_t: sum of the relevant cash flows (net cash flow) i.e., cash inflow – cash outflow, at time t.

   N: number of considered years

   t: the time of cash flow

   r: discount rate

3. Environmental impact: indicating the annual CO2 emission* of each scenario, based on the annual electricity withdrawn from the national grid (uncovered demand).

*CO2 emission reference: https://www.eea.europa.eu/data-and-maps/daviz/co2-emission-intensity-9/#tab-googlechartid_googlechartid_googlechartid_chart_1111

5.1. Condominium scale

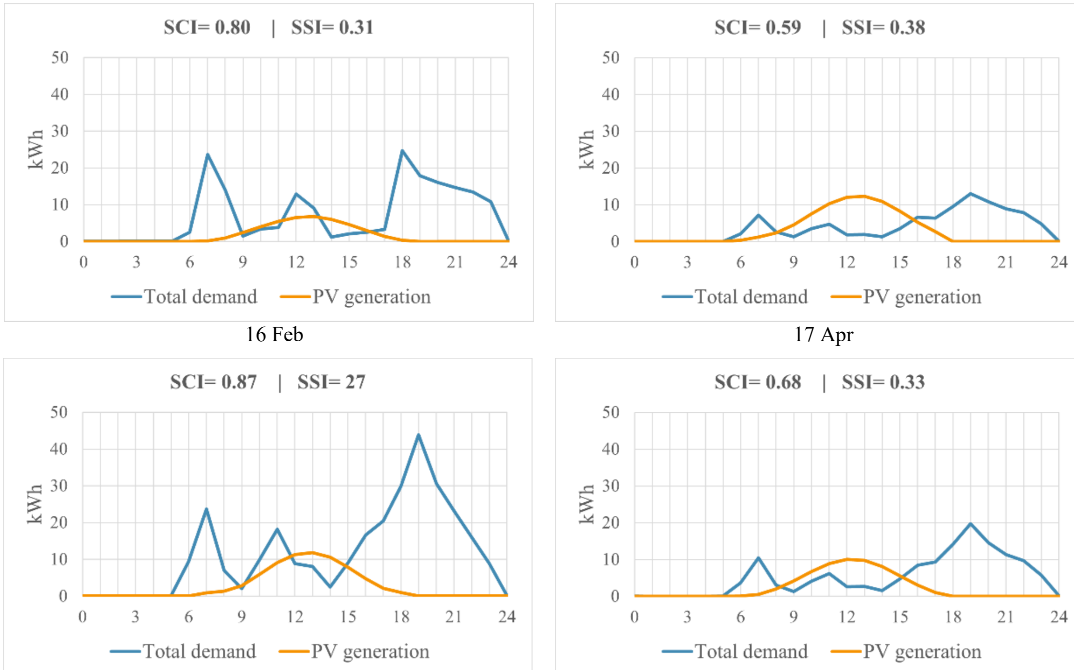


Figure 23 consumption-generation trends for typical weekdays

The typical weekdays of the four seasons are analyzed to understand the production and demand trends considering the installed PV of 20 kWp (Figure 23). The highest SCI is seen in summer when there is a high demand that is not covered by the generation, therefore high UD that results in low SSI as well. The SCI in spring is low due to the high OP compared to the low demand, which is explained by the minimum use of the HVAC system in spring. The installation of a battery system is tested to improve the self-consumption levels by utilizing surplus production. The choice of the battery size follows the test of different sizes, starting from 5 kWh and increasing the size until there is no OP (around 55 kWh). Evaluating the simulated battery sizes from the economic perspective, 20 kWh shows the highest NPV among the other sizes, considering a period of 20 years.

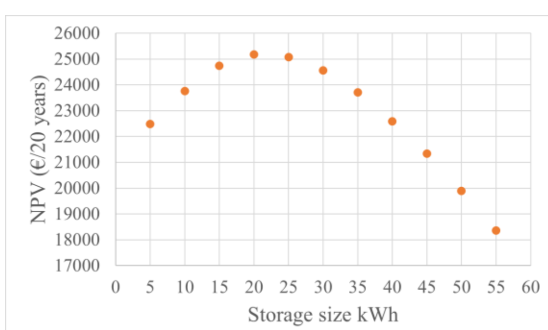


Figure 24 NPV of different storage sizes

Figure 25 illustrates the SCI and SSI values for both 1 POD and 2 PODs cases, considering the difference when a BT system is installed (20 kWh). The installation of a BT system results in higher values since it increases the share of energy by decreasing the mismatch between production and demand, making the overproduction available to the users of the community.

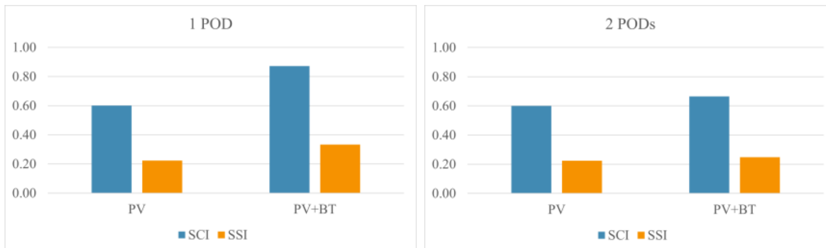
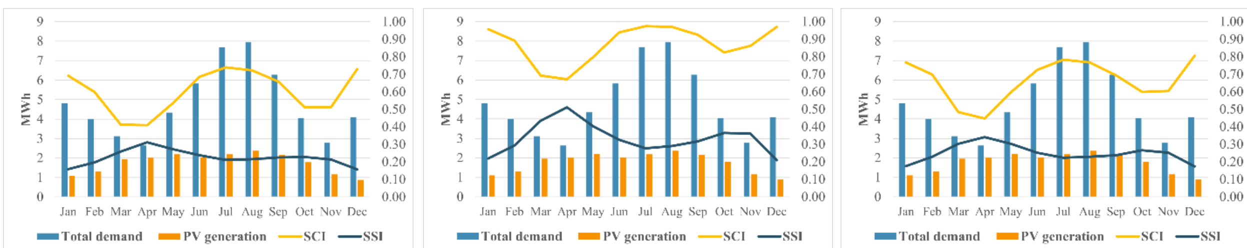


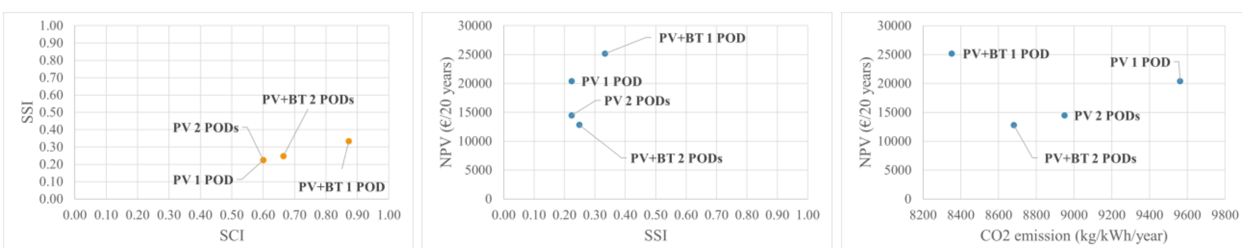
Figure 25 energy indexed for 1 POD and 2 PODs scenarios

The following figures compare the condominium scale scenario considering both 1 POD and 2 PODs cases, with and without batteries.



(a: 1 POD-2 PODs) (b: 1 POD+BT) (c: 2 PODs+BT)

Figure 26 consumption, generation, SCI, and SSI monthly values



(a) (b) (c)

Figure 27 energetic, economic, and environmental result comparison

Figure 26 summarizes the energetic results of 1 POD and 2 PODs cases, showing the monthly demand, generation, SCI, and SSI. Adding BT system results in higher SCI and SSI for both cases, but this difference is very low in 2 PODs compared to 1 POD.

Figure 27 (a) compares both cases from the energetic perspective, showing that aggregating all the end users into one POD with a BT installed results in higher SCI and SSI. Considering the economic and environmental perspectives, 1 POD+BT shows again high NPV, high energy sufficiency, and low CO2 emission* compared to the other cases Figure 27 (b-c).

Analyzing the payback period of each case in Figure 28, we can see the advantage of having the economic incentive of Ecobonus 50%: a tax reduction of 50% for the first 10 years which applies both for the costs of the installed PV and battery system. This shows the importance of government policies in supporting these investments.

The 1 POD case has better results, both with and without BT but has higher returns with BT installed. Overall, it takes 9 years to pay back the investment costs with the presence of Ecobonus 50% incentive for 1 POD+BT, while it takes 12 years for 2 PODs+BT case.

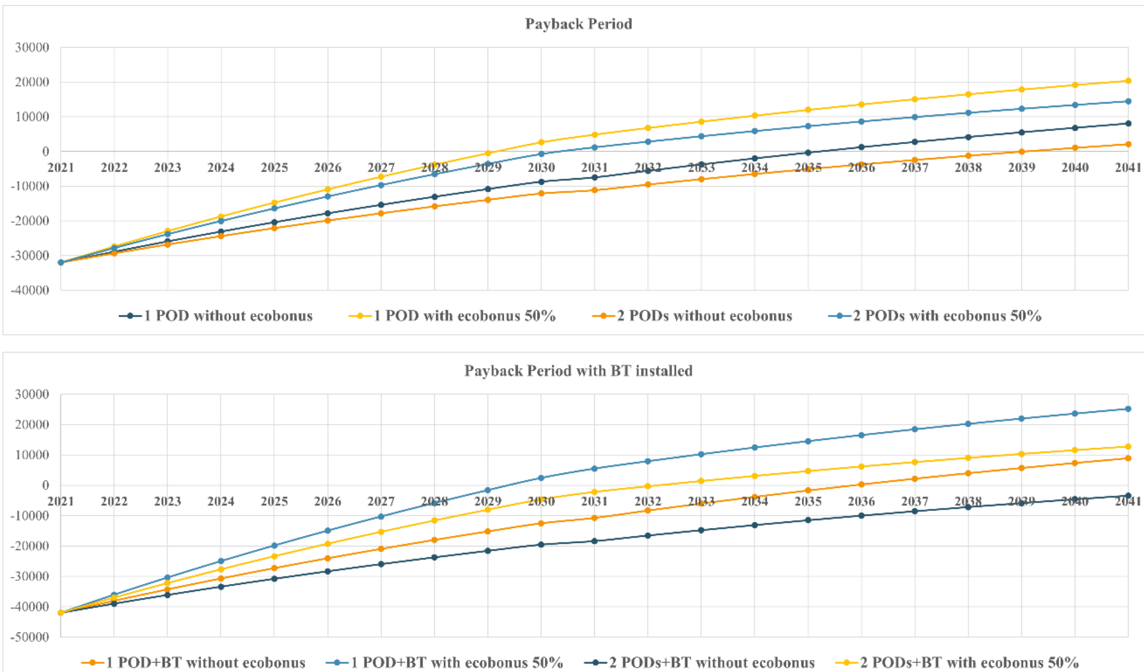


Figure 28 payback period for 1 POD and 2 PODs scenario

5.2. EC with a neighboring building

By analyzing the results of this scenario, we can see the impacts in which a higher energy efficiency building can have for ECs.

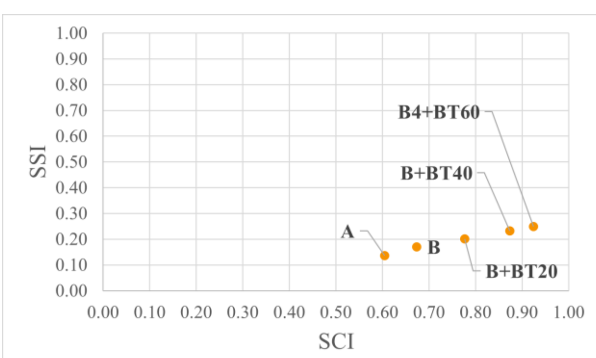


Figure 29 SCI and SSI for EC with a neighboring building

- **A:** 2 non-renovated buildings
- **B:** 2 renovated buildings
- **B+BT20:** case B with 20 kWh battery
- **B+BT40:** case B with 40 kWh battery
- **B+BT60:** case B with 60 kWh battery

Considering the energetic indexes, Figure 29 shows the effects of having renovated buildings for the community (case A and B), which results in 11% of increase in the SCI. Adding a storage system shows even higher results since it improves the self-consumption by utilizing the OP.

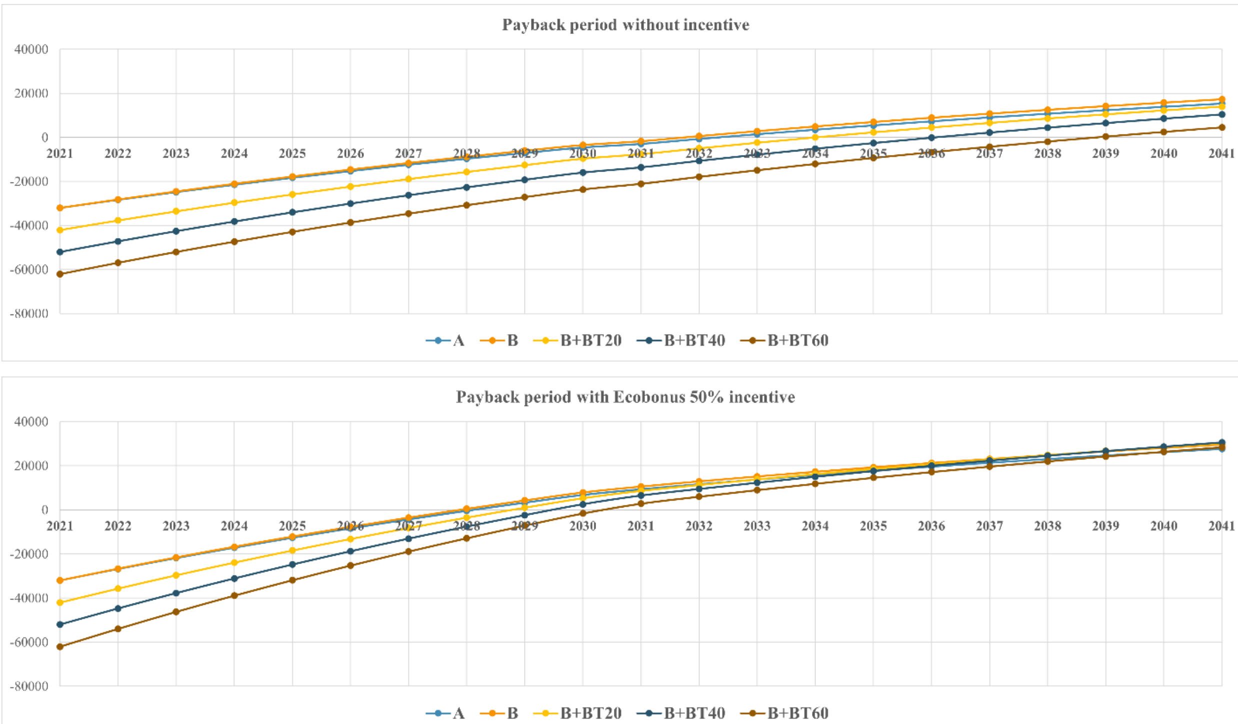
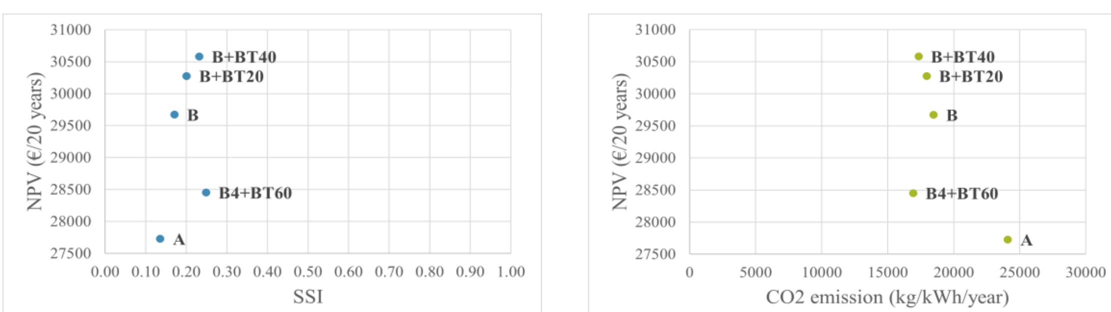


Figure 30 payback periods for EC with a neighboring building scenario (5 cases)

In Figure 30 we can see the advantage of having the incentive of Ecobonus 50% in decreasing the payback period for the 5 cases. Overall, A and B have the shortest payback period (7 years), but considering the economic return, B+BT40 has the highest revenues with a payback period of 8.5 years.



(a) (b)

Figure 31 comparison between economic, energetic, and environmental results for EC with a neighboring building scenario

In Figure 31 we can see the summary of the energetic results (SSI: which indicates the self-sufficiency of the community), economic results (NPV: profitability of project considering the time value of money), and environmental results (GHG emission). Comparing the 5 cases from this summary helps in optimizing the choice of the investment considering the 3 perspectives: energy, economy, environment. From Figure 31 (a) we can see that using a battery storage system of 40 kWh results in the highest NPV and 0.23 for SSI. B+BT60 shows a slightly higher SSI (0.25), but considering the NPV difference between the two storage sizes (40 and 60), 40 is more advantageous. Considering the environmental impacts too, B+BT40 has the most profitable and eco-friendly results.

Overall, the results of this scenario point out the importance of the following inputs for an EC:

•Having a renovated envelop results in better energy efficiency.
•Having a battery storage system increases the energetic, economic, and environmental indexes.
•Sizing the storage system properly is important to optimize the results.

From the energetic perspective, the results of both scenarios analyze the energy efficiency and the potential EC scenarios for the studied building.

From the architectural point of view, it is seen that improving the envelop materials contributes to decreasing the energy needed for space heating and cooling, which in turn affects the results of the designed EC. Altogether, this work shows the importance of having a collaboration between the different disciplines that are intended to achieve more sustainable building stocks.

6. Conclusion

This work aimed to illustrate a comprehensive analysis of the energy consumption profiles starting from a single apartment, which was used later for the design of REC, both in a condominium scale and community scale. The findings throughout the different simulations can answer two different energy concerns: 1) how the building envelop, and HVAC system can play a role in the total building energy demand, 2) how to test the effectiveness of ECs of different scales using real case inputs.

Analyzing the retrofit intervention results, it shows an average decrease of 28% in the total energy consumption, which points to the importance of having an energy-efficient building stock for more sustainable urban districts.

Considering the tested ECs, both scenarios show that battery storage systems have an effective role in increasing the self-consumption levels of the community since the solar energy is intermittent and needs to be optimized for its usage by storing the surplus generation. The batteries are also important in avoiding the high peak demands and in improving grid flexibility, which results in more resilient energy grids. The tested scenarios consider:

- PV of 20 kWp as the RES.
- the residential buildings as the end-users.

Summarizing the analyzed scenarios, in 1 POD case of the condominium scenario, adding batteries showed an increase of 45% in the SCI, and 49% in the SSI. The NPV is also increased by 23% with the presence of a 20 kWh battery. Considering the 2 PODs case, the increase in SCI and SSI showed a constant value of 11% with the presence of a battery, and a decrease of 12% in the NPV, which concludes that aggregating the energy demand of the condominium into 1 POD results in better values than having 2 PODs. In EC with a neighboring building scenario, replacing the buildings with more energy-efficient buildings resulted in a 26% increase in SSI, and a decrease of 23% in CO2 emission, which shows the importance of having renovated and high efficient buildings in achieving more sustainable building stock. In this case, too, adding a battery of 40 kWh to the retrofitted building showed an increase of 36% in SSI and 30% in SCI. Overall, the CO2 emission decreased by 28% when having renovated buildings with a battery of 40 kWh (comparing case A and B+BT40).

In this work, a small-scaled energy community is analyzed. But to reach the goals of lowering global emissions and achieving more sustainable cities, the recasts of the related directives must be considered. One of them is RED II (renewable energy directive 2018/2001/EU). The directive was originally set up in 2001 and amended in 2018. Now there is ongoing progress for the third revision which will include some updates, one of them is rising the percentage of using renewable sources in the overall energy mix from

32% to 40%, which is a target set for 2023. Together with this, the RECs will probably go beyond small-scaled communities with more powerful generation plants and include diverse end-users, e.g., municipality buildings, business centers. To achieve more comprehensive results, it is also important to include different RES and involve mixed end-users. Considering the location of the case study, wind and wave powers can be included and tested for future EC scenarios. Having different end-users increases the optimization of using the generated power because ECs work better when there is more energy share between the end-users, which happens when a user can share its excess energy with another user that has different demand hours and profiles.

The economic analysis is important for the implementation of the examined scenarios. It helps in highlighting the advantage of each scenario and ensuring the economic benefit for the end-users. The illustrated figures also show the importance of having incentives that encourage the end-users to implement an EC. The energy prices used in this work consider the specified current market prices, which can vary over time, so it is important to use proper economic inputs when analyzing a future EC scenario.

Together with the illustrated outcomes, this work contributes also to the use of software that is intended to achieve sustainable design goals by providing integrated tools that work collaboratively for this purpose. Understanding the logic behind the iVN network structure was important to model the right energy network for the analyzed scenario. The configuration of the electricity nodes, their connection order, and the control strategies can give a lot of outcomes that are useful for optimizing the EC model. The numerous simulations that are tested also revealed some useful strategies to construct the right energy network, for example, the connection of the electricity nodes in the case of 2 PODs, as defined in Figure 13 in chapter 3. In that network, the main electricity node can show the residual demand and overproduction after the self-consumed energy by common uses. This in turn gives directly the sharable energy that is available for the other members in the network. Together with this finding, this work contributes to the use of software for modeling small-scaled ECs.

The methodology of this work can give a useful model to test the effectiveness of ECs based on given data, and it can be applied on different scaled ECs.

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