# Using urban building energy simulation tools and geographic information systems to define energy communities

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**Mechanical Engineering**

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# Declaration

I declare that this document is an original work of my own authorship and that it fulfills all the requirements of the Code of Conduct and Good Practices of the Universidade de Lisboa.

# Acknowledgements

First, I would like to express my gratitude towards my supervisors, Ricardo and Diana, for their implication on my work during this period. Thanks for your advice, your constructive contributions and your complete availability for solving questions and doubts. Your support has been essential.

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I feel very lucky to have had the opportunity to get to know Lisbon the way I did. Thanks to everyone I met and made this experience to be such special and delightful. I will come back for sure.

# Abstract

In a context of climate crisis, all efforts should be put on ensuring a sustainable and fair energy transition into renewable and decentralized energy paradigm. Decentralized solar deployment is playing a crucial role in this transition, bringing electricity generation closer to the consumption. Hence, energy communities arise as an innovative and cooperative strategy to share these decentralized energy resources. Aligned with this, urban areas, where electricity consumption is concentrated, are expected to evolve to be self-sufficient by implementing local generation systems such as photovoltaic panels in buildings' roofs.

This thesis develops a modelling framework that uses urban buildings energy modelling to obtain input parameters to assess the potential of energy community creation, by combining building's thermal simulation data and their potential of solar generation in its rooftops.

In this work, different case studies and scenarios have been simulated and analysed. Buildings are simulated in three different scenarios: individual self-consumption, collective self-consumption inside an energy community and collective self-consumption with a central battery storage inside an energy community.

Results demonstrate that self-sufficiency in buildings increase when going from individual self-consumption to collective self-consumption, having the best results when combining diversity of demand profiles. Self-sufficiencies achieved at a community level are 16%, 21% and 34%, respectively for each case study. Moreover, results show that when considering a central battery storage system, self-sufficiency increases 16% on average. Regarding the self-consumption, the average of increase is 35% when considering the storage. However, economic indicators are not favourable in this case.

**Keywords:** Energy communities; Urban building energy simulation; Collective self-consumption; PV solar systems; Central Battery Storage Systems

# Resumo

Num contexto de crise climática, todos os esforços devem ser orientados para assegurar uma transição energética sustentável e justa, para um paradigma de energia renovável e descentralizada. A implementação de sistemas solares descentralizados desempenha um papel crucial nesta transição, aumentando a autossuficiência. As comunidades de energia surgem como uma estratégia inovadora e cooperativa para partilhar estes recursos energéticos descentralizados, especialmente em contexto urbano, onde o consumo de eletricidade está mais concentrado.

Esta tese desenvolve uma metodologia de modelação que, a partir da modelação energética de edifícios urbanos obtém os inputs necessários para avaliar o potencial das comunidades de energia, combinando os dados de simulação térmica dos edifícios e o potencial de geração solar nos seus telhados.

Neste trabalho, diferentes edifícios e casos de estudo foram simulados e analisados para três cenários: autoconsumo individual, sem fazer parte de uma comunidade de energia, e dois cenários integrando uma comunidade de energia: autoconsumo coletivo e autoconsumo coletivo com armazenamento centralizado em baterias.

Os resultados demonstram que a autossuficiência dos edifícios aumenta com o autoconsumo coletivo, obtendo melhores resultados com maior diversidade de perfis de procura. Auto-suficiências alcançadas a nível comunitário são de 16%, 21% e 34%, respectivamente para cada estudo de caso. Adicionalmente, os resultados ao nível da comunidade de energia mostram que, ao considerar um sistema de armazenamento, a autossuficiência aumenta em média 16%. No que diz respeito ao autoconsumo, a média de aumento é de 35% quando se considera o armazenamento. No entanto, neste caso os indicadores económicos não são favoráveis.

**Palavras-chave:** Comunidades de energia; Simulação de energia de edifício urbano; Autoconsumo coletivo; Sistemas solares PV; Sistemas Centrais de Armazenamento de Baterias

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# Glossary

## Acronyms

| | |
|---|---|
| **BESS** | Battery Energy Storage System |
| **CBESS** | Central Battery Energy Storage System |
| **CEA** | City Energy Analyst |
| **CEC** | Citizen Energy Community |
| **EC** | Energy Community |
| **GHG** | Greenhouse Gas |
| **INE** | National Institute of statistics |
| **IRR** | Internal Rate of Return |
| **KPI** | Key Performance Indicator |
| **LEC** | Local Energy Community |
| **NPV** | Net Present Value |
| **O&M** | Operation and Management |
| **OMIE** | Iberian Electricity Market Operator |
| **PV** | Photovoltaic |
| **RE** | Renewable Energy |
| **REC** | Renewable Energy Community |
| **SC** | Self-Consumption |
| **SOC** | State of Charge |
| **SS** | Self-Sufficiency |
| **UBEM** | Urban Building Energy Modelling |

## Variables

| | |
|---|---|
| ${E_{net}}_n$ | Net power (kWh) |
| ${E_{demand}}_n$ | Power demand (kWh) |
| ${E_{generation}}_n$ | PV generation power (kWh) |
| $EC_{demand}$ | EC power demand (kWh) |
| $EC_{surplus}$ | EC power surplus (kWh) |

|  |  |
|---|---|
| $EC_{toGRID}$ | EC power to the grid (kWh) |
| $GRID_{toEC}$ | EC power imported from the grid (kWh) |
| $X_{sharing_n}$ | Surplus sharing coefficient |
| $E_{GRID_n}$ | Building power from the grid (kWh) |
| $SOCmin$ | Minimum SOC level (%) |
| $SOCmax$ | Maximum SOC level (%) |
| $\eta_{charg}$ | Charging efficiency (%) |
| $\eta_{discharg}$ | Discharging efficiency (%) |
| $P_{bat}$ | Maximum CBESS power (%) |
| $B_{cap}$ | Battery capacity (kWh) |
| $B_{level}$ | State of charge of the storage system (kWh) |
| $E_D$ | Energy available for discharge (kWh) |
| $E_C$ | Energy available for charge (kWh) |
| $DISC$ | Discharge (kWh) |
| $CHAR$ | Charge (kWh) |
| $SS_n$ | Building self-sufficiency rate (%) |
| $SS_{EC}$ | EC self-sufficiency rate (%) |
| $SC_n$ | Building self-consumption rate (%) |
| $SC_{EC}$ | EC self-consumption rate (%) |
| $GHG_{index}$ | Greenhouse gases emission factor ($gCO_2/kWh$) |
| $p_b$ | Energy base price (EUR/kWh) |
| $p_{EC}$ | Energy price in EC (EUR/kWh) |
| $p_{surpl}$ | Selling energy price (EUR/kWh) |
| $I_{0n}$ | Initial building investment (EUR) |
| $d$ | Discounted rate (%) |
| $\Delta t$ | Duration of the timestep in hours (h) |

# 1 INTRODUCTION

## 1.1 Motivation

The world is about to enter in a new paradigm as our planet is facing challenges without precedents due to the climate crisis. Change concerns the whole humanity, from institutions to citizens all over the world. Many strategies are being studied and implemented to mitigate climate change such as guaranteeing a sustainable energy transition and reduce the carbon footprint. Nevertheless, each year, Intergovernmental Panel on Climate Change (IPCC) reports are more and more worrying.

Last IPCC report states that the average surface temperature of the Earth will cross 1.5°C over pre-industrial levels in the next 20 years (by 2040), and 2°C by the middle of the century, without sharp reduction of emissions. IPCC has informed that a global net-zero emissions' strategy by 2050 is the minimum required to keep the temperature rise below 1.5°C. All nations, especially the G20 and other major emitters, need to join the net-zero emissions coalition and reinforce their commitments with credible, concrete policies (IPCC |Masson-Delmotte *et al.*, 2021)

This thesis follows the aims to contribute to the decarbonization of cities, implementing new strategies in generation and demand of electricity, to ensure a fair and sustainable energy transition into a renewable and decentralized energy paradigm. According to the Energy Performance of Buildings Directive (EPBD), in Europe, buildings consume 40% of primary energy in the EU and are responsible for about 36% of energy related $CO_2$ emissions (*Revision of the Energy Performance of Buildings Directive (EPBD)*, 2021). This is one of the reasons why the concept of energy communities arises as a transversal solution to guarantee this energy transition in urban areas.

Energy communities (EC) give the possibility to reduce the electricity consumption from the grid with renewable energy production at local scale. When reviewing literature related with energy communities and its definition, challenges arise on assessing the impact of the type and number of buildings which constitute a viable community regarding energy production, self-sufficiency, and investment costs and savings. Therefore, it is important to assess different typologies of EC by developing a tool that facilitates its modelling by using GIS data, combined with construction building-specific data.

Urban building energy models allow to simulate the energy consumption of a large building stock while considering their diversity on construction, geometry and uses. The detailed outputs of this modelling may help evaluate and size energy communities if combined with optimization techniques and geographic information systems. Therefore, the main research question in this thesis is how urban building energy modelling may contribute to evaluate the energy and economic performance of different energy communities' configurations.

## 1.2 Objectives

This thesis focuses on the creation of a modelling framework that calculates the main outputs parameters of energy communities to help decision making for its creation, by combining building's thermal simulation data and their potential of solar generation in its rooftops.

This thesis has the following goals:

- Simulate building stock using UBEM to provide detailed data (hourly resolution) on building's energy needs, for different case studies;
- Develop an energy community model, defining the EC key performance indicators (KPI) by which the EC performance will be assessed and compared;
- Analise different EC configurations and discuss the main differences and impact of number and type of participants.

## 1.3 Contributions

The main contribution of this work is the development of a modelling framework that could assess the implementation potential of energy communities. The model created allows to compare the performance of various building typologies in different energy communities' configurations and case studies.

## 1.4 Structure of the thesis

This thesis is structured in the following chapters:

- Chapter 2 displays the literature review on energy communities and UBEM;
- Chapter 3 presents the methodology followed in this work to obtain energy simulations in buildings and the model created to obtain the energy community output;
- In chapter 4, the different case studies are defined;
- Chapter 5 shows the results and discussion for the cases proposed; and,
- Chapter 6 contains the conclusions and future work of this thesis.

# CHAPTER 2

## 2 LITERATURE REVIEW

In this chapter a literature review is made focusing on energy communities and urban building energy modelling. Research work is done in the definition and performance of Energy Communities at the urban scale, types of EC, tools and methods for analysing its energy and thermal performance, energy consumption and production and building typologies array (number and area). Furthermore, UBEM tools and outcomes focusing on energy communities' studies are also presented.

The present literature review tries to clarify the most relevant aspects of the thesis and set the precedent for the development of the methodology.

### 2.1 Energy communities

Nowadays, two approaches for the definition of energy communities are considered in the European Union legislation: Renewable Energy Community (REC) (Directive (EU) 2018/2001) and Citizen Energy Community (CEC) (Directive (EU) 2019/944).

According to the final Clean Energy Package in EU legislation, Article 2(16) Recast Renewable Energy Directive "Renewable energy community" is described as following:

> *"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, Small and Medium Enterprises 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."*

The Renewable Energy Directive II further states that RECs shall be entitled to produce, consume, store and sell renewable energy, including through renewables power purchase agreements.

In Article 2(11) Recast Electricity Market Directive "Citizen energy community" is described as following:

> *"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."*

**Table 1. Main differences between REC and CEC (RESCOOP | Dorian Frieden et al., 2019)**

| **REC** | **CEC** |
|---|---|
| Limited membership | No limited membership |
| Proximity requirement of effective control | No geographic limitation |
| All sources of renewable energy | Electricity only |
| 100% ER | Technology neutral |

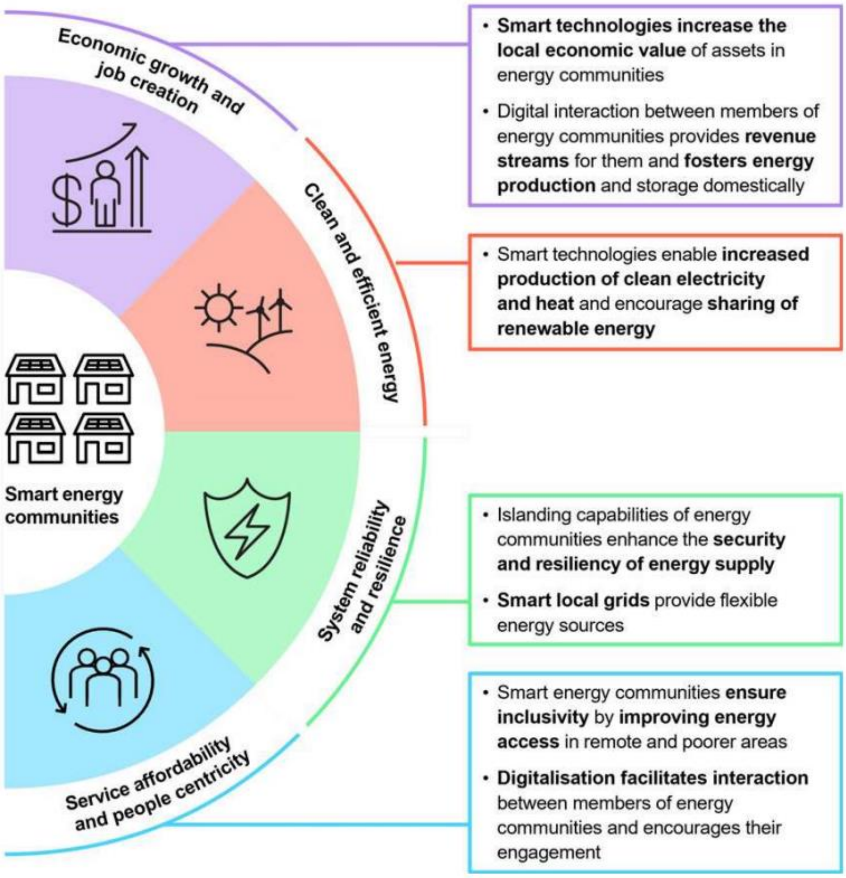
Regarding Portugal, the Decree Law 162/2019 (DL 162/2019 (25 Oct)) states the following regulatory framework for energy communities:

*a) "self-consumption of renewable energy, allowing the self-consumer - in addition to producing and consuming, may also have activities of sharing, storing and selling surplus energy, being a scheme in which one or more renewable energy production units (UPAC) may be linked to one or more points of consumption;*

*b) renewable energy communities (RECs), allowing consumers to find themselves in a close neighbourhood relationship, i.e. in a relationship of physical proximity, and to be able to collectively organize and carry out collective self-consumption with each other or to establish an energy community – two forms of organization that are distinguished from each other: in the former through an internal regulation defining rights and obligations, and in the second through a cooperative legal entity or company owned by both self-consumers and other entities involved in the self-consumption project. Thus, the recipients of DL 162/2019 (25 Oct) are both individual consumers, as well as consumer groups - organized collectively or in energy communities (incl. condominiums, urban areas/neighbourhoods, business parks, agricultural units, industrial units, parishes, and municipalities), whose infrastructure is in a relationship of neighbourhood and proximity of the energy project."*

Energy communities could be paving the way to more inclusive energy systems by giving citizens democratic control and ownership over their energy supply. Furthermore, energy communities can also cooperate with system operators to increase the resilience of the energy grid. This resilience is achieved by taking a full advantage of the large number of active households involved, benefiting from the aggregation of demand response, and offering flexibility to the system operator. (IEA, 2021)

According to the IEA, in Figure 1 are shown the benefits of energy communities. These advantages encompass integrative solutions that contribute to a cleaner and more sustainable energy generation, as well as can be used as a tool to guarantee inclusivity in energy access. Furthermore, these systems also increase the resiliency and security of energy supplies.



- **Smart technologies increase the local economic value** of assets in energy communities
- Digital interaction between members of energy communities provides **revenue streams** for them and **fosters energy production** and storage domestically

- Smart technologies enable **increased production of clean electricity and heat** and encourage **sharing of renewable energy**

- Islanding capabilities of energy communities enhance the **security and resiliency of energy supply**
- **Smart local grids** provide flexible energy sources

- Smart energy communities **ensure inclusivity** by **improving energy access** in remote and poorer areas
- **Digitalisation facilitates interaction** between members of energy communities and encourages their engagement

**Figure 1. Benefits of smart energy communities (IEA, 2021)**

Energy communities exhibit a diversity of purposes, governance models, size and owned assets. However, the identification of two general models is made. The first one concerns communities with large or medium scale with central generation, and the other with small, distributed generation. Besides, energy communities can have feature characteristics of these two models, thus is called hybrid model. Figure 2 illustrates the different types of models described.

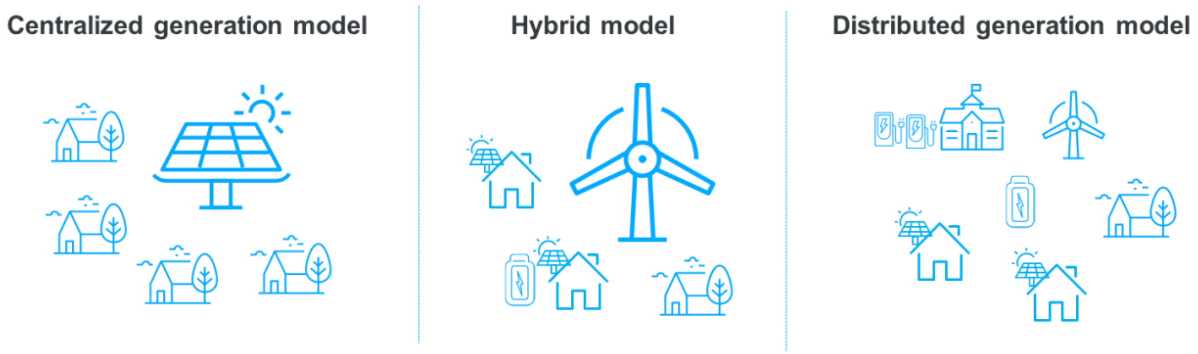


**Figure 2. Illustration of centralized, hybrid and distributed generation models (European Commission,2021)**

### 2.1.1 Datasets, models and tools when defining energy communities

One of the main issues when defining energy communities is the collection and analysis of the necessary data. In (Kazmi *et al.*, 2021) this problem is addressed, the focus on the paper is to provide a detailed overview of publicly available datasets, models and tools that can be used to optimize design and operation of Local Energy Communities (LEC)

Data availability is crucial for the success of the operation of energy communities, both during the design and the operation phase. In Figure 3 is presented an overview of the use of datasets in each phase of the process for LEC.

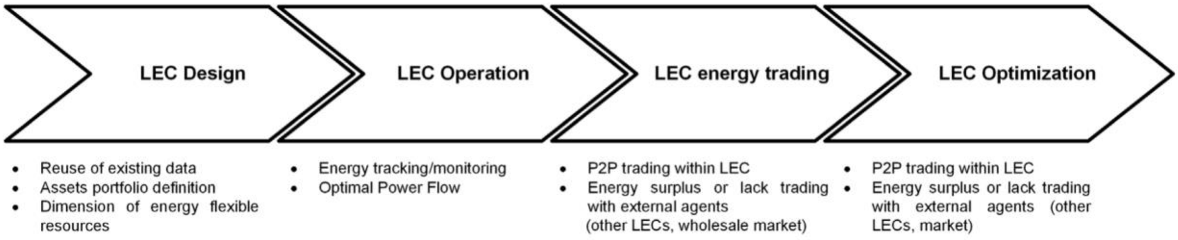


**Figure 3. LEC data use cases. (Kazmi *et al.*, 2021)**

According to (Kazmi *et al.*, 2021), the following datasets are necessary when defining an energy community, which can be distinguished in two different categories:

- Demand side data (Residential building and commercial building energy demand): For instance, the SustData dataset (Pereira *et al.*, 2014) provides measurements for 50 residential units in Portugal over a period of 1144 days;

- Climate related data (Observed and forecast weather conditions, historic weather conditions and long-term forecasts for climate change). For instance, several services, including the NSRDB and others, provide Typical Meteorological Year (TMY) data to explain the climate of a specified region, often in the EPW format which can be used with tools such as EnergyPlus (Fumo, Mago and Luck, 2010).

On the other hand, data can also have origin in models, which allow the generation of data for specific scenarios. The following models are being highlighted from (Kazmi *et al.*, 2021):

- For electricity generation: PVWatt.

  Developed by the National Renewable Energy Laboratory, provides a browser-based PV system model that estimates the electricity output and economic costs of grid connected PV energy systems, based on geographic location, technical characteristics of the PV system and local market conditions (National Renewable Energy Laboratory).

- Storage models: OSESMO.

  Provides a battery model (for Lithium-ion and flow batteries) and calculates the optimal charge–discharge strategy in 15-minute time periods using linear programming, in order to minimize the end-user monthly bill (Moskalik A *et al.*, 2018).

- Optimization of energy communities: System Advisory Model (SAM) and OPEN

  Created by NREL, SAM provides end-to-end decision-making support for micro-grids and energy communities. SAM incorporates different models of renewable energy systems such as solar PV systems, energy storage systems, etc. and can therefore be used to obtain data for the entire community considering different renewable and flexible assets installed (Blair *et al.*, 2018).

  Oxford University’s Energy and Power Group’s Open Platform for Energy Networks (OPEN) presents in (Morstyn *et al.*, 2020) a python toolset for modelling, simulation and optimization of smart local energy systems. The platform is implemented in python with an object-oriented structure, providing modularity and allowing it to be easily integrated with third-party packages.

Case studies are presented in (Morstyn *et al.*, 2020), demonstrating how OPEN can be used for a range of smart local energy system applications due to its support of multiple model fidelities for simulation and control. Figure 4 reports the platform structure, showing a universal modelling language (UML) class diagram. OPEN has four important base classes: a smart local energy system application is built around an Energy System object, which has a list of Asset objects defining the loads and DERs, a Network which the Asset objects are embedded within, and an upstream Market which the Network is connected to.

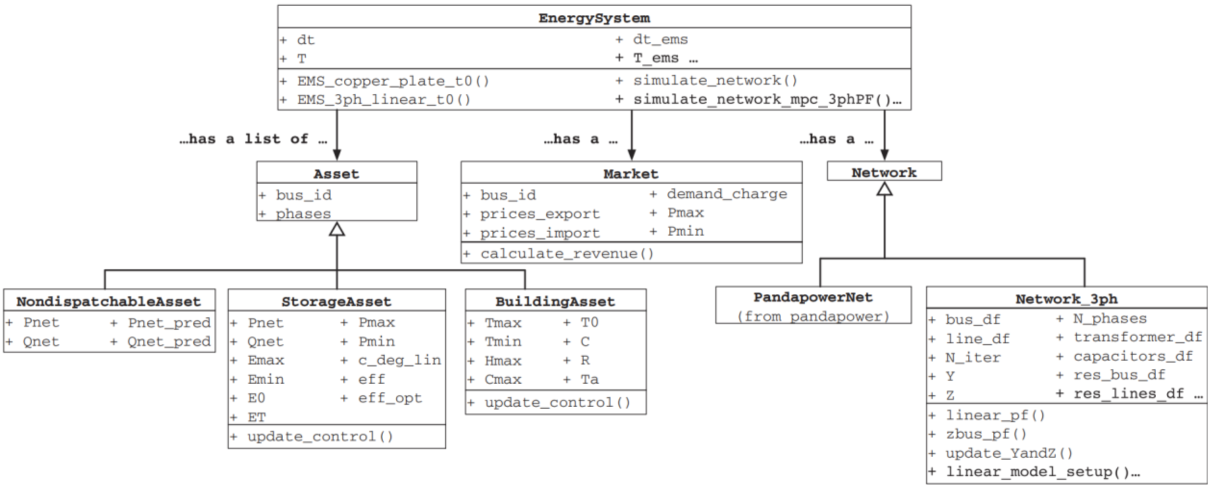


**Figure 4. Platform structure in (Morstyn *et al.*, 2020)**

### 2.1.2 Regulatory framework for energy communities

As is it told in (Sousa *et al.*, 2019), the continuous integration of distributed energy resources from rooftop solar panels, storage and control devices, along with the advance in information and communication technology devices are transforming a share of electricity consumers into prosumers. This new scenario raised the need of a regulatory framework for the implementation of energy communities in Europe.

Nowadays, regulatory framework for energy communities can differ depending on the country of the EU, since each country had the freedom to transpose the European directive according to country specific context. In (Sousa *et al.*, 2019), all the trends and challenges of this EU framework are described and analysed. In order to better understand how trading works, the following definition has been highlighted:

*“Peer-to-peer trading” is defined by the REDII (Revision of the Renewable Energy Directive) as “the sale of renewable energy between market participants” by specific means including “the automated execution and settlement of the transaction”. This may occur “either directly between market participants or indirectly through a certified third-party market participant, such as an aggregator”.* (Dorian Frieden *et al.*, 2020)

Also, it is stated that electricity markets still perform resource allocation and pricing based on the conventional hierarchical and top-down approach of power system management although power systems are evolving to a more decentralized management. This conventional approach makes prosumers behave as passive receivers.

Peer-to-peer trading, also known as P2P defines a decentralized structure where all peers cooperate with what they have available for commons-based producing, trading or distributing a good or service. The current paradigm has the drivers to conduct the transition towards P2P markets in order to bring prosumers into power system operational practice.

In (Sousa *et al.*, 2019), different cases of P2P market structures are presented: full P2P market, community-based market design and hybrid P2P market, where it is concluded that the hybrid P2P market design is the most suitable in terms of scalability, giving room for all others P2P designs to interact.

Furthermore, in (Sousa *et al.*, 2019) it is concluded that there are conditions to deploy P2P markets in co-existence with existing market structures. The current market is also the key to achieve a smooth and manageable transition towards P2P markets, as energy communities help to ensure the security and resiliency of energy supplies and provide flexible energy sources. Therefore, these are also benefits for the current and centralized market, and this should not be seen as a problem.

### 2.1.3 Optimization cases

Energy communities can be established from different approach strategies, with different goals and as such, with different outputs. For instance, main priority could be high self-consumption, but also optimization of costs. Therefore, there is a high number of solutions and combinations of main energy communities' parameters depending on the strategy used.

In the following lines, are presented three case studies found when reviewing literature that consider different approaches in the definition and performance of energy communities. These research works will be considered when defining energy communities in this thesis.

- **Electricity allocation in energy communities**

In (Fina, Monsberger and Auer, 2022), it is presented an analysis based on ten fictitious renewable energy communities, out of which five are equipped with privately owned PV systems

The two possible forms of allocating electricity between participants in (Fina, Monsberger and Auer, 2022) are static and dynamic allocation. Static allocation means that a fixed key is applied to the distribution of the total amount of available electricity between the participants within a community. This means that if an energy community has 10 participants, each participant is eligible for one-tenth of the available electricity at each timestep. Dynamic allocation implies no fixed shares for individual customers but rather allocates the available PV electricity such that an optimal usage is guaranteed.

Results in (Fina, Monsberger and Auer, 2022) show that dynamic allocation increases the efficiency of electricity use compared to static allocation electricity. Electricity expenditures are reduced for all participants while at the same time, more PV electricity is consumed locally.

Indicating that dynamic allocation of available generation is preferable to static distribution key. It is also concluded that realistic assessment of a residential energy community's profitability can be provided by a well-developed estimation model with proper assumptions as well as by a detailed simulation. This model is also defined as easily transferable to other geographical locations.

- **Optimal sizing with battery storage**

In (Weckesser *et al.*, 2021a) an extensive study of Renewable Energy Communities and their potential impact on the electric distribution grid is presented. The main aim is to investigate the impact on distribution grids of different energy community configurations, different operating strategies and different battery placements.

Results in (Weckesser *et al.*, 2021a) show that when the battery is located at the beginning of the feeder, then the energy community does not impact the observed minimum and maximum voltage. The largest voltage deviations could generally be observed when the battery was located at the end of the feeder. Furthermore, the optimal installed capacities of photovoltaics with a communal battery were in the configuration with households and one large commercial costumer. This study was solely focused on electricity, future work could extend this study to include communal heating and/or interactions with charging of electric vehicles.

- **Mixed-integer linear programming optimization model**

In (Braeuer *et al.*, 2022) it is developed a mixed-integer linear programming (MILP) optimization model for assessing the implementation of multi-energy systems in an energy community in multi-family buildings with a special distinction between investor and user. Therefore, this model includes multiple technological options such as photovoltaic (PV), combined heat and power (CHP), heat pump (HP), and electric vehicle (EV) charging.  The model determines the optimal energy flows on an hourly basis for one representative year matching the households' electricity and heating demand. The model is implemented in Matlab and solved with the CPLEX solver. Figure 5 shows the possible energy flows and the technological components.

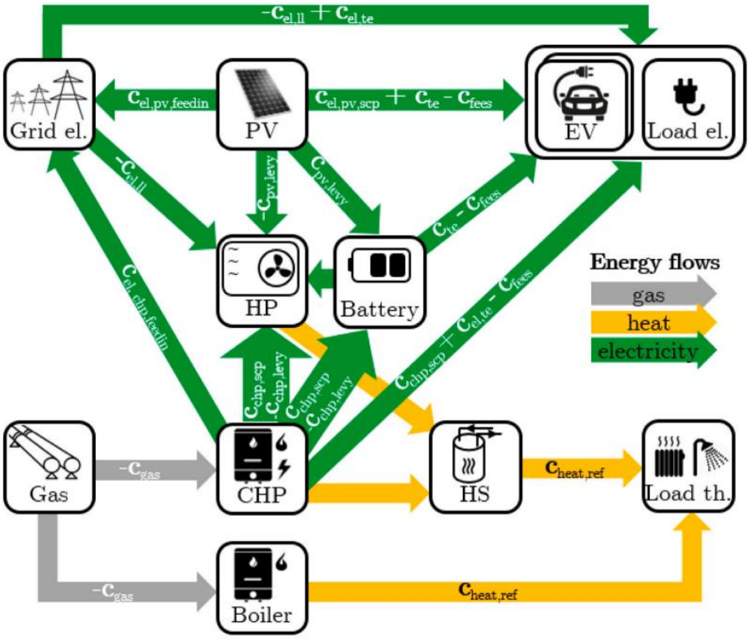


**Figure 5. Energy flows (Braeuer *et al.*, 2022)**

Regarding the results, self-sufficiency ratios of more than 90% are observable for systems with combined heat and power plants and heat pumps. Finally, the results show the strong influence of the heat demand on the system layout. It is also stated that the implementation of energy communities differs greatly by country. This model is developed based on the German Tenant Electricity Law. Nevertheless, this is a precedent for international practitioners, policymakers and the investigation on other energy community frameworks in detail.

## 2.2 Urban building energy modelling (UBEM)

Building energy consumption plays a significant role in global energy supply and demand. Building energy use currently accounts for over 40% of total primary energy consumption in EU (Masson-Delmotte *et al.*, 2021). Nevertheless, significant energy savings can be achieved in buildings if they are properly designed, constructed, and operated.

According to Pordata, in 2020, the percentage of electricity consumption for domestic usage was 29% in Portugal, and 27% in Lisbon (PORDATA - Consumo de energia eléctrica: total e por tipo de consumo). Besides, according to the Portuguese General Direction of Energy and Geology (DGEG), in 2020 36% of natural gas consumption in Lisbon was for domestic use. Here is where relies the importance of influencing in the domestic consumption of energy, following initiatives to reduce energy consumption in buildings and creating a new path of generation and consumption of energy in cities. ´

In (Ang, Berzolla and Reinhart, 2020), Urban building energy modelling (UBEM) is defined as a bottom-up, physics-based approach to simulate the thermal performance of new or existing neighbourhoods and cities. The goal of UBEMs is to provide data-driven insights for different urban-level use cases, such as urban planning and new neighbourhood development, stock level carbon reduction strategies, and buildings-to-grid integration.

Taking this into account, UBEM arises as an essential line of research to achieve the reduction of energy consumption in buildings and model its behaviour. Building energy efficiency can provide key solutions to energy shortage and carbon emissions (Cao, Dai and Liu, 2016). Thus, the achievement of realistic models of energy performance in buildings is essential to achieve main objectives regarding energy efficiency in buildings. Several challenges associated with the implementation of building energy modelling includes data availability, data inconsistencies, data scalability, data integration, geocoding and data privacy issues (Ali et al., 2020).

Also, urban building energy modelling is described in (Hong *et al.*, 2020) as follows:

*“Urban building energy modelling refers to the computational modelling and simulation of the performance of a group of buildings in the urban context, to account for not only the dynamics of individual buildings but more importantly, the inter-building effects and urban microclimate. The goal is to provide quantitative insights (e.g., annual, or seasonal energy use and demand, potential of renewable power generation) to inform urban building design and operation, as well as energy policymaking.”*

Urban building performance metrics include near-term operational efficiency (e.g., energy use and demand at the daily, monthly, and yearly time frames), short-term demand response (e.g., electric load shedding and shifting at the minute to hour time frame), long-term sustainability (e.g., GHG emissions, impacts of climate change on energy demand at the year to decade time frame), and event-driven resilience (e.g., impact of extreme weather events such as heatwaves and wildfire on energy use, power supply, and occupant health at the day time frame).

According to (Hong *et al.*, 2020), UBEM can also estimate the potential of renewable power generation from photovoltaics (PV) or wind turbine systems located rooftops or integrated into building facades. For electric vehicle (EV) charging that uses the building power system, UBEM can integrate the EV loads into the building's overall energy demand.

Also, depending on user cases, UBEM can have different spatial and temporal scales. UBEM can cover spatial scales from tens of buildings in a city block to hundreds or thousands of buildings in a district, and to tens or hundreds of thousands of buildings in an entire city. UBEM typical covers temporal scales from an hour to a day, a week, a month, a year, and one or multiple decades (Hong *et al.*, 2020).

Figure 6 illustrates the key components of a UBEM ecosystem, including datasets, simulation workflows, results, and stakeholder metrics to support decision making.

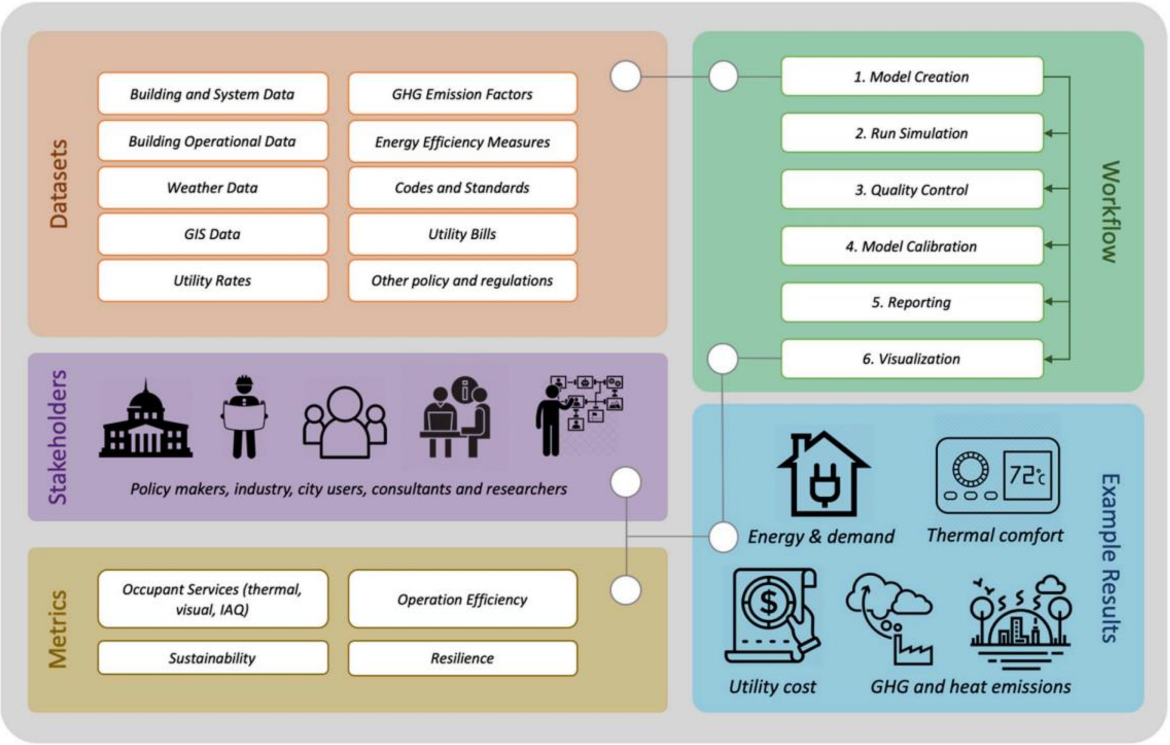


**Figure 6. Urban Building Energy Modelling, overview (Hong *et al.*, 2020)**

The following statements from (Hong *et al.*, 2020) are highlighted and considered some important issues in urban building energy modelling:

- UBEM is not about scaling up energy modelling from one individual building to many buildings in a linear fashion; it is about capturing the dynamic and complex interconnection and interdependencies between urban buildings and the urban environment;

- UBEM also simulates on-site renewable energy generation (mainly PV) and district energy systems serving a group of buildings taking advantage of their thermal load diversity. Considering urban buildings as part of urban systems (a system of systems) will enable greater performance than just considering them the simple sum of individual buildings. UBEM is a powerful tool that provides simulation and analysis for urban energy planning and design, carbon emissions from buildings, and local building energy or GHG regulations and code compliance;

- Due to the limited publicly available information of individual buildings in cities, lots of default data and many assumptions must be made to conduct detailed energy modelling. Therefore, there are inherent uncertainties with UBEM results. Calibrating the urban building energy models is usually based on annual (rather than monthly or hourly) energy use data of individual buildings.

### 2.2.1 Different applications using UBEM for decision making

In the following lines, there are highlighted different type of applications and methodologies that use UBEM. All of them are seen as useful and consistent references to the development of the methodology and decision making in this thesis.

**- Multi-detail building archetype**

In (Monteiro *et al.*, 2017), multi-detail archetypes of buildings are generated and applied to a neighbourhood in Lisbon. Five scenarios with different numbers of archetypes considered. The methodology used for the simulation of these archetypes is divided in 3 main steps: Classification, parametrization and modelling (Figure 7).

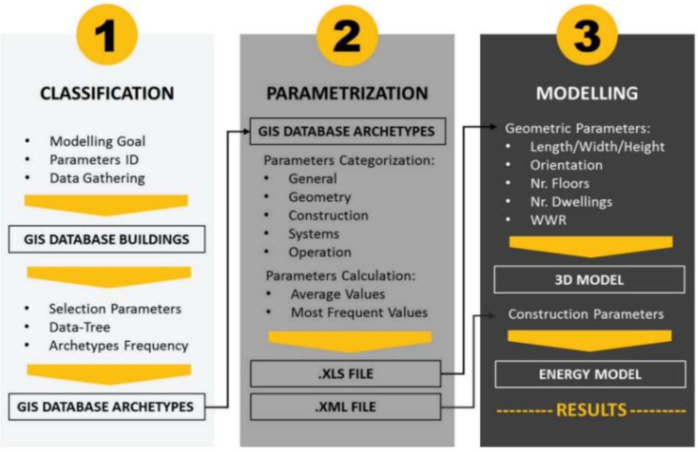


**Figure 7. Methodology (Monteiro *et al.*, 2017)**

The results show how the need to create new archetypes depends highly on the variability of the parameter being used to divide a set of buildings. If almost all buildings in a determined subset corresponding to an archetype share the same parameter, then there is no need to subdivide the archetype as the variation in the energy demand will be very small. However, if that is not the case, the changes in the estimated total energy consumption may be significant.

This case is highlighted because of the importance on the definition of different archetypes for buildings, to get more realistic results.

**- Multi-scale modelling for planning and decision making**

In (Ali *et al.*, 2020) , the Irish building stock is used to map building energy performance at multiple scales. The case uses deep learning algorithms to predict results. Prediction results are then used for spatial modelling at multiple scales from the individual building level to a national level. Furthermore, these maps are coupled with available spatial resources (social, economic, or environmental data) for energy planning, analysis, and support decision-making.

The methodology devised in this study proposes a generalized solution for energy planning and decision making at multiple scales. The solution uses limited available resources such as energy performance certificates, geographical, spatial, census, and retrofit project data to predict the building energy performance. The study uses a data driven technique to geocode building stock data for spatial mapping. The methodology is illustrated in Figure 8.

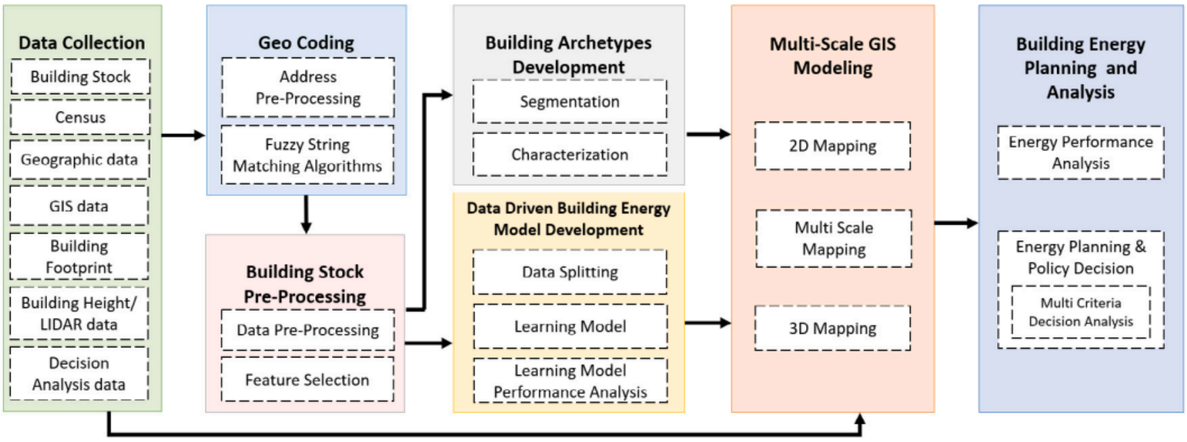


**Figure 8. Methodology multi-scale GIS modelling (Ali *et al.*, 2020)**

The generalized data-driven methodology could produce maps of residential building energy performance at multiple scales, which will aid the planning process. To develop an energy efficiency footprint of the urban building stock and henceforth, identify priority areas to implement energy efficiency solutions.

The modelling results identify clusters of buildings that have a significant potential for energy savings within any specific region. Geographic Information System-based modelling aids stakeholders in identifying priority areas for implementing energy efficiency measures. Furthermore, the stakeholders could target local communities for retrofit campaigns, which would enhance the implementation of sustainable energy policy decisions (Ali *et al.*, 2020).

This study is highlighted because it stands out a multi-criteria methodology that takes different factors into account, as well as is needed in the creation of energy communities.

**- Prioritizing urban planning factors**

In (Yu *et al.*, 2021), the study proposes a holistic approach integrating GIS techniques, building energy modelling, and a global sensitivity analysis to prioritize eight key urban planning factors on the community energy performance based on a building energy dataset. The dataset, including urban planning and building information, was first established using GIS techniques and validated using survey data.

The residential energy performance model at the community scale was developed using the clustering tree structure of residential building prototypes and building performance simulations. A combined data-driven and global sensitivity analysis approach was further applied to prioritize the impacts of eight vital urban planning factors on energy use intensity and peak load intensity.

A case study of 1963 residential communities in Shanghai revealed that, for the energy performance of these communities, the floor area ratio and building coverage ratio are the most influential factors, followed by the maximum height and high-rise proportion having a relatively low impact but higher than other factors. Overall, the proposed holistic approach generates robust insights into urban-scale residential energy performance, which can effectively inform urban planners to achieve more energy-efficient regulatory planning. (Yu *et al.*, 2021)

The reason why this case has been also highlighted is because it stands out the parameters that are more relevant on the building energy performance when using building energy dataset.

### 2.2.2 City Energy Analyst (CEA)

City Energy Analyst (CEA) is a computational framework for the analysis and optimization of energy systems in neighbourhoods and city districts. The framework allows analyzing the energy, carbon and financial benefits of multiple urban design scenarios in conjunction to optimal schemes of distributed generation. For this, the framework integrates time-dependent methods for building energy performance simulation, conversion and storage technologies simulation, assessment of local energy potentials, bi-level energy systems optimization and multi-criteria analysis.

City Energy Analyst offers energy demand/supply analysis for buildings at a district scale to support decision making of energy efficiency planning (Fonseca *et al.*, 2016) .

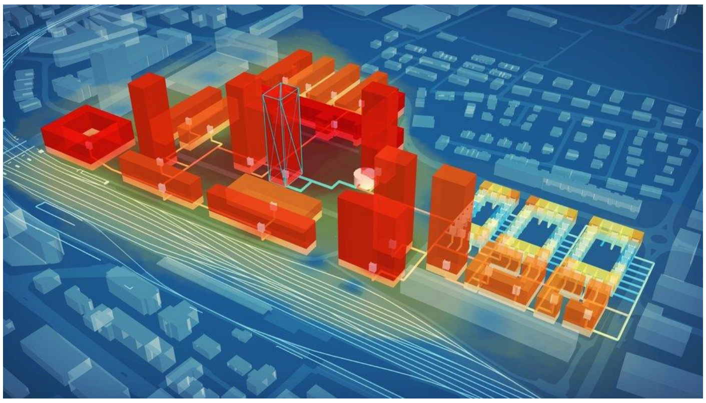


**Figure 9. City Energy Analyst (City Energy Analyst)**

City Energy Analyst was developed by ETH Zürich and Singapore in 2016. It contains seven data bases (weather, urban environment, energy services, conversion, distribution, systems and targets) and six modules (demand, resource potential, system technology, supply system, decision analysis). It is developed in the open-source programming language Python v2.7 and built as an extension of the Geographic Information System ArcGIS v10.3. (Ferrando *et al.*, 2020)

#### 2.2.2.1 Calculation of energy demand in buildings

In (Fonseca et al., 2016), it is described the framework used in CEA. Regarding the demand module, the final energy demand of buildings is decomposed in manifold end-uses and estimated in an hourly basis at both qualitative (i.e., temperature, voltage requirements) and quantitative levels (i.e., power intensity and mass flow rates). This allows addressing end-uses such as space heating and cooling, domestic hot water, appliances and lighting.

#### 2.2.2.2 Calculation of solar radiation and PV potential in buildings

As mentioned in (Fonseca et al., 2016), the resource potential module aggregates physical models for the assessment of endogenous energy sources. The hourly solar insolation in rooftop areas is estimated with an algorithm of Fu et al.(1999), implemented in ArcGIS 10.3. The algorithm models solar trajectory, topographic obstructions (i.e., buildings and terrain), atmospheric effects, latitude and elevation.

For the analysis realized in (Fonseca *et al.*, 2016), roof-top areas are discretized in *k* rectangular surfaces of 2×2 m and calculated the solar insolation at their centroid in the horizontal plane. Figure 10 shows the isolation for buildings in this study.

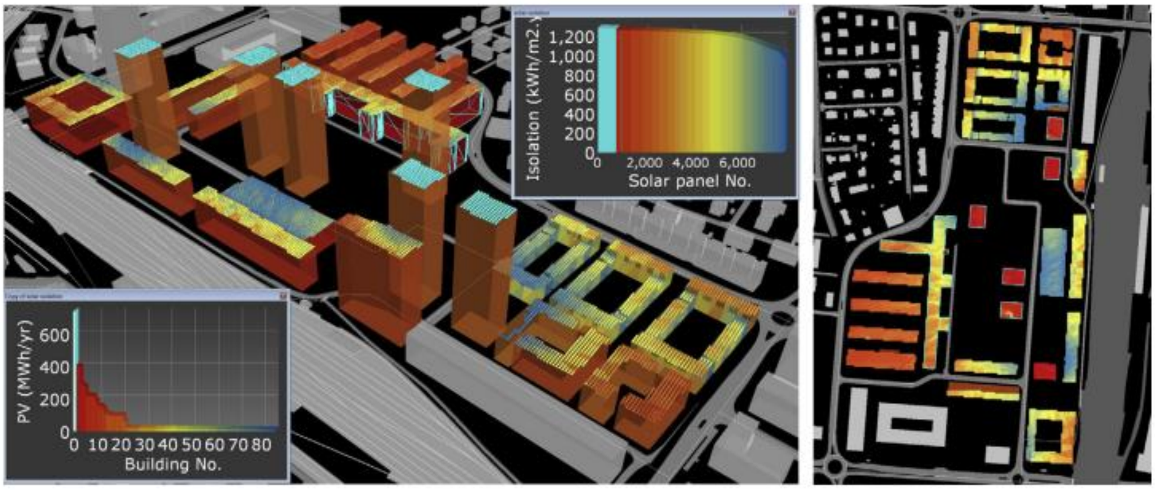


**Figure 10. Case study for isolation in building roofs. CEA (Fonseca et al., 2016)**

Appendix A on this work, gathers the data flow used by CEA when calculating demand and generation outputs.

# CHAPTER 3

## 3 METHODOLOGY

This chapter presents the methodology followed in this thesis. The first step is gathering all the necessary data from the buildings as it is described in the section 3.1. Then, having collected the data, it is used an urban building energy modelling tool to achieve building energy demand (3.2) and photovoltaic energy production for each building (3.3). To obtain the buildings demand, it is necessary defining buildings' construction standards, end-uses and energy supply t. Also, the solar radiation in roofs and the configuration of the PV systems are used to calculate the photovoltaic energy production potential in each roof surface. Then, in section 3.4 are presented the main parameters considered to evaluate the performance of the energy community and the different scenarios considered on this study. Besides, the performance and sizing for the battery system is also considered in this section. Section 3.5 introduces the Key Performance Indicators that are used to compare the results for the different scenarios and case studies. Finally, in section 3.6 the modelling framework created that allows to achieve the KPIs is presented, using the modelling outputs and calculating the performance for the energy community as defined in section 3.4.

With all mentioned above, Figure 11 shows the methodology used in this thesis, which is applied in the three different case studies presented in Chapter 4.

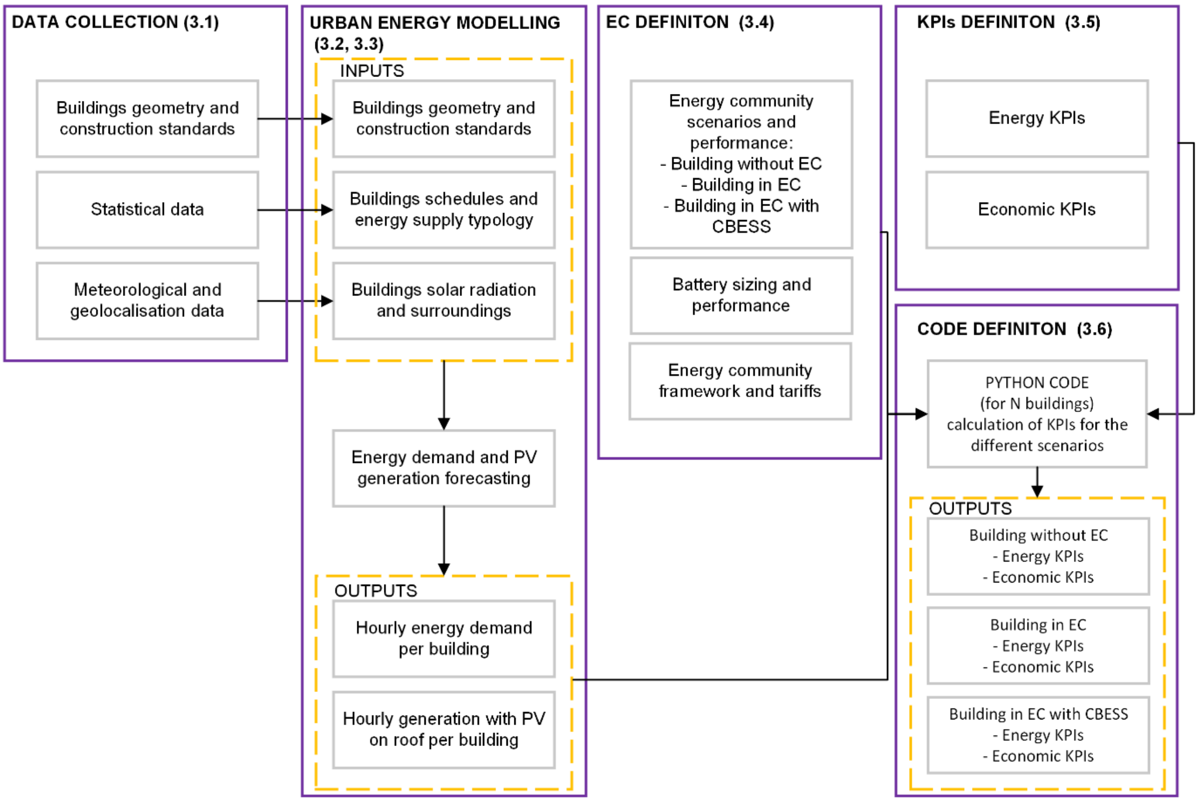


**Figure 11. Methodology**

## 3.1 Data collection

To perform the urban building energy modelling, the following data needs to be gathered:

- Geolocation data for the studied area (topography of the terrain);
- Meteorological data for the studied area (weather files with solar radiation based on satellite data);
- Geometry and construction standards of the buildings (height, number of floors above and below ground, floor area, roof area, year of construction, transmittance values);
- Data for buildings archetypes (type of building use, schedules of equipment and lighting use, occupation, energy supply characterisation).

## 3.2 Characterisation of UBEM

The energy performance of the buildings is modelled through the software City Energy Analyst (CEA), with its framework defined in (Fonseca *et al.*, 2016).

Regarding the building data, the inputs for City Energy Analyst are shapefiles that contain the building plans, construction standards and uses for buildings in a certain area. The tool (QGIS) has been used to create the inputs for CEA. Therefore, one shapefile was created assigning the building geometry and the construction standards for each building, and the other shapefile assigns the typology of use for each building.

Both shapefiles are created following the step 3.1 Data collection, with data from the building geometry and construction standards. In the same way, to assign the type of use and the energy supply for each building, data from the Portuguese statistical institution (INE) is used (INE, 2021).

Other necessary inputs for CEA are the meteorological data and the surroundings for the selected area. For this aim, meteorological data is collected from Energy Plus Weather Data (EnergyPlus) and surroundings are created in CEA with data from Open Street Maps (OpenStreetMap).

After having all these inputs, the demand forecasting for each building is run. CEA creates one file per building with the hourly energy demand data for a year in .csv format. Figure 12 illustrates the inputs and outputs in the building demand forecasting with CEA.

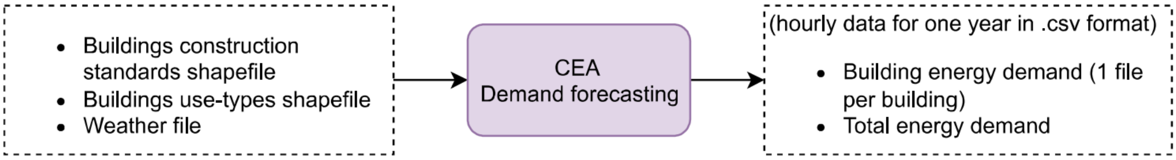


**Figure 12. CEA demand forecasting**

## 3.3 Photovoltaic potential

This methodology considers the implementation of photovoltaic panels in every building as long as their roofs achieve a minimum radiation per year (which is a constraint in the calculation). With this, it is important to mention that economic factors are not being considered when implementing photovoltaic panels, its viability is only restricted by radiation parameters. The photovoltaic potential for each building is also calculated through CEA with the definition of the parameters mentioned below.

### 3.3.1 Solar radiation on roofs

With the geolocation data and the weather file, City Energy Analyst calculates the horizontal solar radiation for the rooftops of all buildings. The output files are also hourly and in .csv format.

### 3.3.2 Minimum threshold

By defining the minimum threshold, City Energy Analyst is going to consider panels only on surfaces that receive a yearly horizontal radiation above a pre-defined value in kWh/m$^2$/yr.

### 3.3.3 Area of the roof covered

In City Energy Analyst, the rooftop area percentage covered by panels can be chosen by the user. Therefore, within this feature, it can be modified the total area that will be covered by panels leaving apart non usable parts of the roof.

### 3.3.4 Tilt angle

PVGIS tool (*PVGIS Photovoltaic Geographical Information System*) is used to decide the slope of the panels. The inclination of the panels will be the one with the highest yearly in-plane solar irradiation (kWh/m2).

### 3.3.5 PV panels features

Features of the photovoltaic panels are defined by CEA and can be also edited by the user. Main characteristic parameters are nominal efficiency (%), dimensions (m), capacity (kWp), nominal operating cell temperature (ºC) and cell maximum power temperature coefficient (1/ºC).

Figure 13 illustrates the inputs and outputs in the building photovoltaic potential with CEA.

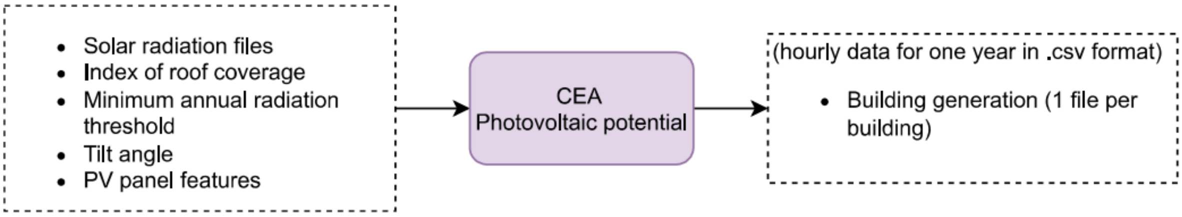


**Figure 13.Photovoltaic potential in CEA**

## 3.4 Definition of energy communities

After having the demand and generation files for each building from section 3.2 and 3.3, this section establishes framework for the development of energy communities within these buildings. Therefore, here are defined the parameters that are used in the code to obtain the main outputs that define energy communities.

As energy communities can be configurated in different ways, this work considers three different scenarios. As mentioned in section 3.3, it is considered that all buildings have PV generation, that means that all have self-consumption of energy. Therefore, the three different scenarios defined are the following:

- **Scenario 1: Building without EC**
  This scenario considers that the building profits only from the PV generation in its own roof, without being part of an energy community. Grid consumption occurs when the demand cannot be covered by PV generation. Also, when there is surplus from the PV generation, these are injected to the grid.

- **Scenario 2: Building in EC**
  This scenario considers that the building profits from the PV generation from its own roof, and shares or receives solar generation surpluses from the rest of the buildings that are part of the energy community. The percentage of shares ($X_{sharing_n}$) that each building can receive in each timestep is proportional to the building demand and it is defined in equation (6).
  When the EC still has demand after sharing surpluses, it is supplied by the grid. Also, when the EC still has surpluses, these are injected into the grid.

- **Scenario 3: Building in EC with Central Battery Energy Storage System (CBESS)**
  This scenario considers that the building electricity demand can be covered with its own self-consumption, with surpluses from other buildings and with energy from the CBESS. The logic in this case is to cover first its own self-consumption and surpluses from other buildings, and then with electricity from CBESS. The CBESS is charged and discharged with surpluses and demand from the EC.
  Then, in this case, the interaction with the grid occurs after using the storage system. When the EC still has demand after using the CBESS, consumption from the grid occurs. Also, when the EC still has surpluses after using the CBESS, these are injected into the grid.

The electricity fluxes for each building, depending on the scenario considered, are presented next.

The hourly electricity net $E_{net_n}$ for each building, *n*, is calculated as follows,

$$E_{net_n}(t) = E_{demand_n}(t) - E_{generation_n}(t) \quad \text{[kWh]} \qquad (1)$$

This way, for the scenario 1 (building without EC), $E_{net_n}$ will represent the electricity balance of the building with the grid.

For scenarios 2 and 3, as well as the buildings which will be part of the energy community, the demand and surpluses at an energy community level are calculated in (2) and (3). For each timestep, when $E_{net_n}$ is positive means that the building would need electricity from the grid. Therefore, this value is added as a demand for the EC. In the same way, when $E_{net_n}$ is negative means that the building has surplus of electricity, and this is added as surplus to the EC.

$$if\ E_{net_n}(t) \geq 0\ ;\ EC_{demand}(t) = \sum_1^N E_{net_n}(t)\ \text{[kWh]} \qquad (2)$$

$$if\ E_{net_n}(t) < 0\ ;\ EC_{surplus}(t) = \left|\sum_1^N E_{net_n}(t)\right|\ \text{[kWh]} \qquad (3)$$

At a community level, the electricity demand will be firstly covered with surpluses from the EC and when demand cannot be satisfied, this electricity will be supplied by the grid. Equation (4) defines the calculation for the electricity that would be exported to the grid and (5) defines the electricity that the energy community would still need to import from the grid, in each timestep.

$$if\ \ EC_{surplus}(t) \geq EC_{demand}(t)\ ;\ EC_{toGRID}(t) = EC_{surplus}(t) - EC_{demand}(t) \quad \text{[kWh]} \qquad (4)$$

$$if\ EC_{surplus}(t) < EC_{demand}(t)\ ;\ GRID_{toEC}(t) = EC_{demand}(t) - EC_{surplus}(t) \quad \text{[kWh]} \qquad (5)$$

At a building level, the percentage of EC surpluses, $X_{sharing_n}(t)$, that corresponds to each building is proportional to the building demand and is defined in (6). Therefore, the electricity that each building would need from the grid after sharing the surpluses, $E_{GRID_n}(t)$, is calculated in (7).

These calculations require $E_{net_n}(t) \geq 0$. Otherwise, a negative value for $E_{net_n}(t)$ means that the building does not need electricity from the grid.

$$X_{sharing_n}(t) = \frac{E_{net_n}(t)}{EC_{demand}(t)} \qquad \text{[\%]} \qquad (6)$$

$$E_{GRID_n}(t) = max\ (E_{net_n}(t) - X_{sharing_n}(t) * EC_{toGRID}(t); 0) \quad \text{[kWh]} \quad (7)$$

In case (7) is negative, $E_{GRID_n}(t) = 0$, since this value cannot be negative. This case would mean excess of electricity for the energy community and would be considered in (4).

### 3.4.1 Storage modelling (CBESS)

As mentioned in (Li *et al.*, 2022), energy communities still face the issue of not being able to consume their own surpluses due to the decoupling of generation and demand. In that way, storage systems arise as an effective solution to solve this problem.

According to (Terlouw *et al.*, 2019), there is an increasing interest in Community Energy Storage (CES) systems, due to beneficial economies of scale and optimal storage sizes in CES, compared to Home Energy Storage (HES). CES can be defined as an energy storage system located at the consumption level which can perform several applications with a positive impact for both end users and the network (Parra *et al.*, 2016). It is expected that CES will offer distributed applications and energy trading in electricity markets more efficiently, since the controlling of CES is expected to be more convenient than the controlling of HES (Parra *et al.*, 2017). In (Roberts, Bruce and MacGill, 2019), the scenarios modelled with CBESS achieve higher self-consumption and self-sufficiency values than when considering individual storage.

Therefore, the methodology applied also analyses the scenario of adding a Central Battery Energy Storage System (CBESS) to the energy community. This way, surpluses from energy community are stored in the CBESS and only when the storage system is full, these surpluses go to the grid. In the same line, the electricity demand from buildings would be fist covered by the energy stored in CBESS and when the storage available is not enough to cover the demand, it will be supplied by electricity from the grid.

In this section, it is defined the methodology for sizing and defining the CBESS. In Table 2, the assumptions made for the CBESS definition are gathered and based on literature review data from (Mulleriyawage and Shen, 2020). The review is made for Lithium-ion batteries as recommended in (Terlouw *et al.*, 2019) for central energy storage.

**Table 2. Assumptions for CBESS**

| Parameters | ID | Values | Sources |
|---|---|---|---|
| Minimum State of Charge | $SOCmin$ | 10% | (Mulleriyawage and Shen, 2020) |
| Maximum State of Charge | $SOCmax$ | 95% | (Mulleriyawage and Shen, 2020) |
| Efficiency for charge and discharge | $\eta_{charg}$ ; $\eta_{discharg}$ | 95% | (Mulleriyawage and Shen, 2020) and (Naumann *et al.*, 2015) |

Regarding the battery sizing, the criteria used is to cover the average demand from the grid with supply from the CBESS, as it is done in (Terlouw *et al.*, 2019) by assuming that the battery is extensively used and that there is one daily battery discharge. Hence, this leads to a minimum of 365 cycles per year.

The battery capacity, $Bcap$, is defined following the specifications above. According to the maximum and minimum SOC parameters for the battery system, in (8) and (9), respectively. $Bmin$ and $Bmax$ refer to the minimum and maximum stored energy in the CBESS.

$$Bmin = Bcap * SOCmin \qquad \text{[kWh]} \qquad (8)$$

$$Bmax = Bcap * SOCmax \qquad \text{[kWh]} \qquad (9)$$

It is considered that the limit of power rates for charging and discharging the battery is 1/3 of the battery capacity, as applied in (Mulleriyawage and Shen, 2020). So, $P_{bat}$ is defined as the maximum power rate in each charge and discharge in kW.

$$P_{bat} = \frac{B_{cap}}{3} \qquad \text{[kW]} \qquad (10)$$

When the energy community is demanding electricity and there is enough energy in the battery, it is allowed a discharge to occur; when the PV panels are producing more energy than the energy community demand and the battery is not at the maximum level, the charge is allowed to occur.

Then, the algorithm in Table 3 is applied to calculate the performance of the CBESS in each timestep. It is divided in 5 steps: In step 1 and 2 the energy available in the battery in timestep *t* is calculated, considering the restrictions of being always between 10-95% level of SOC; Step 3 calculates the discharge of the battery considering the restrictions of $P_{bat}$ and the discharge efficiency; In the same line, step 4 calculates the charge of the battery considering also the power restriction and the charge efficiency; In step 5, the new state of charge for the battery is calculated depending if it is in charge or discharge mode, calculating the kWh stored in each timestep with $B_{level}$.

**Table 3. Algorithm for performance of the CBESS**

| Step | Description | Parameter | Equation |
|---|---|---|---|
| 1 | Energy for discharge available in t | $E_D(t)$ | $E_D(t) = max(\, B_{level}(t-1) - Bmin(t); 0)$ [kWh] (11) |
| 2 | Energy for charge available in t | $E_C(t)$ | $E_C(t) = max(\, Bmax(t) - B_{level}(t-1); 0)$ [kWh] (12) |
| 3 | Discharge of the battery in t | $DISC\ (t)$ | $if\big(E_D(t) > GRID_{toEC}(t)\big)\ ;$<br>$DISC\ (t) = min\left(\frac{GRID_{toEC}(t)}{\eta_{discharg}};\ P_{bat} * \Delta t\right)$ [kWh] (13)<br>$else\ \ ;$<br>$DISC\ (t) = min\left(\frac{E_D(t)}{\eta_{discharg}};\ P_{bat} * \Delta t\right)$ [kWh] (14) |
| 4 | Charge of the battery in t | $CHAR\ (t)$ | $if\big(E_C(t) > EC_{toGRID}(t)\big)\ ;$<br>$CHAR\ (t) = min\big(EC_{toGRID}(t) * \eta_{charg}\ ;\ P_{bat} * \Delta t\big)$[kWh] (15)<br>$else\ \ ;$<br>$CHAR\ (t) = min\big(E_C(t) * \eta_{charg}\ ;\ P_{bat} * \Delta t\big)$ [kWh] (16) |
| 5 | kWh stored in the battery in t | $B_{level}\ (t)$ | $if(DISC\ (t) > 0)\ ;$<br>$B_{level}\ (t) = max\big(B_{level}(t-1) - DISC\ (t)\ ;\ Bmin(t)\big)$ [kWh] (17)<br>$else\ \ ;$<br>$B_{level}\ (t) = min\big(B_{level}(t-1) + CHAR\ (t)\ ;\ Bmax(t)\big)$ [kWh] (18) |

Therefore, for each timestep is calculated the electricity needed from the grid ($GRID\_B_{toEC}$, Equation 19) and the electricity that the energy community would export to the grid ($EC\_B_{toGRID}$, Equation 20). At a building level, the electricity consumed from the grid would be proportional to the building demand in each timestep ($E\_B_{GRID_n}$, Equation 21).

$$GRID\_B_{toEC}(t) = max(GRID_{toEC}(t) - DISC\ (t)\ ;\ 0) \quad \text{[kWh]} \quad (19)$$

$$EC\_B_{toGRID}(t) = max\left(EC_{toGRID}(t) - CHAR\ (t)/\eta_{charg}\ ;\ 0\right) \quad \text{[kWh]} \quad (20)$$

$$E\_B_{GRID_n}(t) = X_{sharing_n}(t) * GRID\_B_{toEC}(t) \quad \text{[kWh]} \quad (21)$$

### 3.4.2 Energy community framework and tariffs

When assessing the viability of energy communities, legislative frameworks regarding energy communities need to be known. Energy community policies can vary depending on the country, then, it is essential to get to know the current framework for the cases that are being studied. In the same way, it is also necessary to know how the pricing for selling surpluses and the purchase from the grid is regulated.

These frameworks will establish the way of how the energy community is configurated and how is the energy trading with the grid.

## 3.5 Key Performance Indicators

Key performance indicators are used as useful parameters to evaluate feasibility and performance of the project of study in different areas. In this section are defined the KPIs used to evaluate the performance for the different configurations considered for energy communities.

### 3.5.1 Energy Key Performance Indicators

As done in (Villar, Neves and Silva, 2017), energy KPIs are chosen regarding two different parameters:

I. Regarding the total consumer demand: Self-Sufficiency rate, GHG savings.
II. Regarding the PV total production: Self-Consumption rate.

The Self-Sufficiency rate (SS) represents the ratio of demanded electricity provided from PV panels and battery in relation with the total electricity demand. This parameter provides information of how much of the total electricity demand is covered by the renewable source, the PV generation in this case. It is calculated as presented in equation (22).

$$SS_n \ = 1 - \frac{\sum_{t=1}^{8760} E_{grid_{n,t}}}{\sum_{t=1}^{8760} E_{demand_{n,t}}} \qquad [\%]\ (22)$$

Where $E_{grid_n}$ represents the building consumption from the grid. Depending on the scenario considered (building without EC, building in EC or building in EC with CBESS), $E_{grid_n}$ is defined by $(E_{net_{n,t}}) > 0$ , $E_{GRID_{n,t}}$ or $E\_B_{GRID_{n,t}}$, respectively.

At an energy community level, the self-sufficiency rate is calculated in equation 23, where $Egrid_{EC,t}$ represents the consumption from the grid for the whole EC. Depending on the scenario considered (building in EC or building in EC with CBESS), $Egrid_{EC,t}$ is defined as $GRID_{toEC_t}$ or $GRID\_B_{toEC_t}$, respectively for each scenario.

$$SS_{EC} = 1 - \frac{\sum_{t=1}^{8760} Egrid_{EC,t}}{\sum_{1}^{N} (\sum_{t=1}^{8760} E_{demand_{n,t}})} \qquad [\%]\ (23)$$

Self-consumption rate is also a key performance indicator calculated. This rate refers to the consumed electricity produced by PV panels in relation with the total production. Self-consumption ratio provides information about the allocation of the electricity surpluses.

At a building level, self-consumption is defined in (24).

$$SC_n \ = 1 - \frac{\left| \sum_{t=1}^{8760} (E_{net_{n,t}}) < 0 \right|}{\sum_{t=1}^{8760} E_{generation_{n,t}}} \qquad [\%]\ \ (24)$$

At an energy community level, the self-consumption rate is calculated as defined in equation 25. Depending on the scenario considered (EC without or with CBESS), $Esurplus_{EC,t}$ is defined by $EC_{toGRID}$ or $EC\_B_{toGRID}$.

$$SC_{EC} \ = 1 - \frac{\sum_{t=1}^{8760} Esurplus_{EC,t}}{\sum_{1}^{N} (\sum_{t=1}^{8760} E_{generation_{n,t}})} \quad [\%]\ (25)$$

The savings on Greenhouse Gas (GHG) emissions are also evaluated in this work. Electricity from the grid has inherent GHG emissions, as well as large percentage of its production is with fossil fuels. In the scope of this work, electricity produced by the photovoltaic panels is considered that has an emission factor of zero GHG. Savings on GHG for each scenario are calculated considering the electricity demanded from the grid in each case and comparing them with the base case in which all the electricity demanded comes from the grid. Equation 25 defines the calculation of the GHG savings where $E_{DEMAND}$ represents the EC yearly electricity demand and $E_{GRID}$ is the yearly electricity consumption from the grid for each EC scenario (without or with CBESS).

The emission factor considered for the electricity from the grid $(GHG_{index})$ is 270.42 $gCO_2$/kWh (Origem da Energia - Particulares | EDP), which is the last annual value for the electricity from EDP in Portugal.

$$GHG\ savings \ = GHG_{index} * (E_{DEMAND} - \ E_{GRID}) \quad [gCO_2]\ (26)$$

### 3.5.2 Economic Key Performance Indicators

Regarding Economic KPIs, Net Present Value and Internal Rate of Return are analysed. Annual energy costs, savings and PV income are also assessed for the different scenarios.

The energy cost for the base case, which is the building without PV, it is calculated as in Equation (27)

$$E_{Costbase_n} = \sum_{t=1}^{8760}(E_{demand_{n,t}} * p_{b_t}) \quad \text{[EUR]} \quad (27)$$

Where $E_{demand_{n,t}}$ is the electricity building demand and $p_{b_t}$ is the price of energy for the base scenario, in the building without being part of an EC.

The $E_{Cost_n}$ for each building is calculated for each scenario with the electricity grid consumption and the correspondent energy price. Equation (28) is used to calculate the annual cost of electricity in the different scenarios considered (building without EC, building in EC or building in EC with CBESS). Energy prices are defined in section 4.3.2 Tariffs.

$$E_{Cost_n} = \sum_{t=1}^{8760}(E_{GRID_{n,t}} * p_{EC_t}) \quad \text{[EUR]} \quad (28)$$

Having the costs defined, percentage of savings for each scenario is calculated in Equation (29),

$$\%savings = \frac{E_{Costbase_n} - E_{Cost_n}}{E_{Costbase_n}} \quad [\%] \quad (29)$$

Incomes due to the sale of surpluses to the grid are also included in the model and calculated in Equations (30) and (31). Equation (30) defines the building incomes when it is not part of an EC (scenario 1). $E_{surplus_{n,t}}$ represents the building's surpluses and price for the sale of the surpluses in each timestep is defined as $p_{surpl_t}$.

$$INCOME_n = \sum_{t=1}^{8760}(E_{surplus_{n,t}} * p_{surpl_t}) \quad \text{[EUR]} \quad (30)$$

In the scenarios of the building in EC and EC with CBESS, incomes are defined proportionally to the surpluses of each building regarding the total surpluses generated at the energy community level. Equation (31) defines the income of buildings, being $EC_{surplus}$ the energy community surpluses injected to the grid in each scenario (without or with CBESS).

$$INCOME_n = \frac{\sum_{t=1}^{8760} E_{surplus_{n,t}}}{\sum_{t=1}^{8760} EC_{surplus}} * \sum_{t=1}^{8760}(EC_{surplus} * p_{surpl_t}) \quad \text{[EUR]} \quad (31)$$

Net Present Value represents the net profit generated by an investment, calculated from the discounted sum of future costs and revenues. The project is considered feasible when the NPV is greater than zero with a considered discount rate. The total length for the NPV calculations is 25 years, as this period is the PV panels lifetime (Villar, Neves and Silva, 2017; An et al., 2020). NPV is defined in Equation (32).

$$NPV_n = \sum_{t=0}^{T} \frac{Revenue_n}{(1+d)^t} - I_{0n} \quad \text{[EUR]} \quad (32)$$

Where $Revenue_n$ comes either from the building energy cost savings and the sales of the excess electricity to the grid, $I_{0n}$ is the investment cost, $T$ is the number of years considered, $d$ is the discount rate.

Regarding the PV investment, it has been assumed 1100 €/kWp installed, as implemented in (Weckesser *et al.*, 2021b). The discount rate used is 5%. It is based on (Barbour *et al.*, 2018), where energy communities with central batteries are assessed. Inflation is not considered, while a 0.8%/year PV panel degradation rate is implemented, as the efficiency of the solar PV system decreases by about 20% during its useful time of 25 years (An et al., 2020; Villar, Neves and Silva, 2017). Neither Operations and Management (O&M) costs are considered, since the values found in the literature of around 1 to 3% of the investment costs were considered negligible (An *et al.*, 2020). However in case this value were higher, they would influence the calculations, by decreasing the NPV and thus would need to be considered.

Investment costs in scenario 3 considers a Li-ion central battery with a cost of 337.4 €/kWh with a lifetime period of 15 years as used in (Weckesser *et al.*, 2021b) for a community battery.

Internal Rate of Return estimates the discount rate at which the NPV equals zero. Projects are considered feasible when $IRR > d$, with $d$ being the discount rate. The higher the IRR, better is the investment (Drury, Denholm and Margolis, 2011). IRR can be calculated using Equation (33) with the same parameters mentioned above.

$$\sum_{t=0}^{T} \frac{Revenue_n}{(1+IRR)^t} - I_{0n} = 0 \quad (33)$$

## 3.6 Code definition

To be able to calculate all the parameters described above for as many buildings as it is desired, a code in Python has been implemented.

This code has as inputs the outputs from City Energy Analyst (defined in sections 3.2 and 3.3), which are the energy demand and the solar generation file for each building simulated. Therefore, by applying the operations defined in 3.4 and considering different scenarios for the buildings (without EC, in EC without CBESS, or in EC with CBESS), the code calculates the KPIs defined in 3.5.

With these results, two different types of analysis can be made. One is the analysis at the building level, comparing the different Key Performance Indicators for each scenario. The other analysis is at the energy community level, comparing the different KPIs obtained when the energy community uses CBESS or not.

Figure 14 illustrates the structure of the code developed. First, energy demand data and generation data are merged. With this, each scenario (building without EC, building in EC and building in EC with CBESS) is calculated. For the third scenario, data from the CBESS is added as an input for the code. Finally, building and EC level KPIs are the outputs.

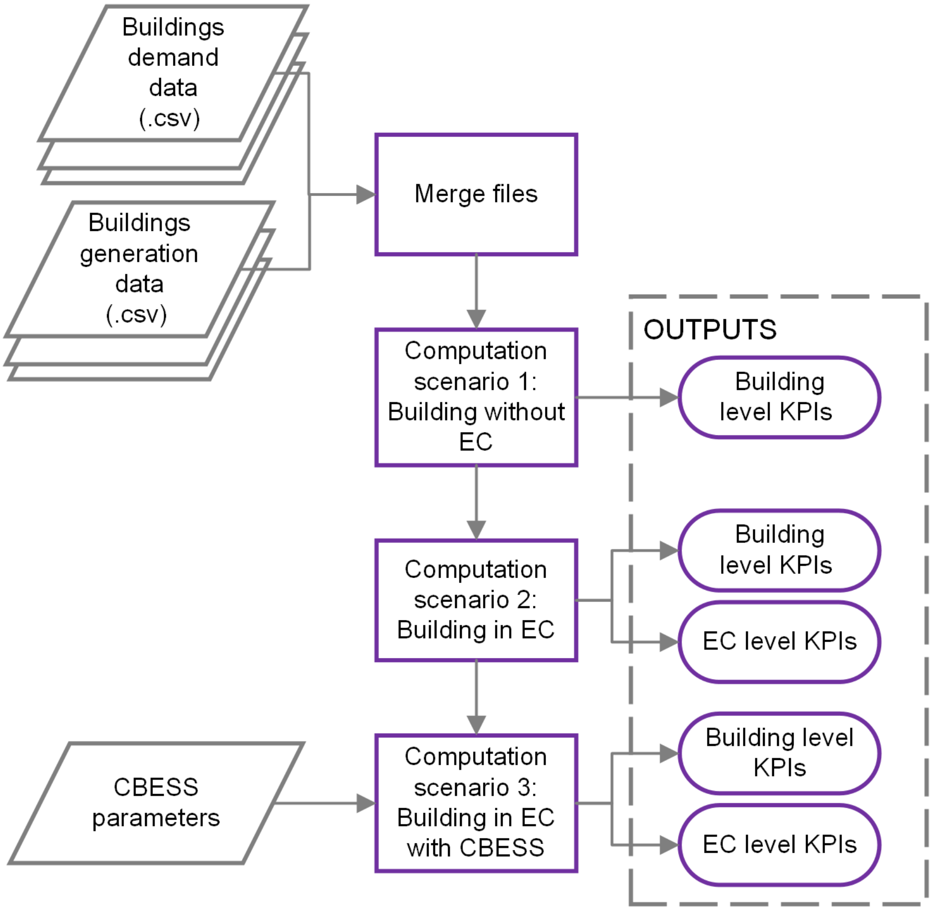


**Figure 14. Code framework**

# CHAPTER 4

## 4 CASE STUDIES

In this chapter the definition of the different case studies developed in this work is presented. By applying the methodology defined in chapter 3, the case studies defined here are evaluated and their results are presented in chapter 5.

Case studies defined in this thesis take place in the neighbourhood of Madre de Deus, in Lisbon. Therefore, in section 4.1, the energy consumption for buildings is characterized and section 4.2 characterizes the PV production in roofs. Besides, in section 4.3 can be found how energy communities are characterized in Portugal.

Having all the specific data collected for Madre de Deus neighbourhood, in section 4.4 the different case studies evaluated in this work are presented.

**Figure 15. Madre de Deus neighbourhood, in Lisbon, Google Maps view**

## 4.1 Energy consumption characterisation

The characterisation of the energy consumption is used to estimate the buildings energy demand. The energy consumption in buildings depends on its constructive solutions, internal loads, appliances and lighting demand, usage patterns, comfort expectations, and HVAC and renewable energy production systems. In this thesis, it is aimed to model and define the energy demand on the buildings used for the definition of energy communities.

Nevertheless, as each building has its own particularities, here is where the difficulty of Urban Building Energy Modelling to define the energy consumption for several buildings arises. In this line, building archetypes appear as a solution to define the energy consumption in buildings. As mentioned in (Monteiro *et al.*, 2017), building archetypes are theoretical buildings created by a composite of several characteristics found within a category of buildings with similar attributes.

Besides, building archetypes also need to reflect the type of consumption derived from the type of use of the building. Research is done to define representative consumption profiles, based on data from national statistics institutions such as INE (INE, 2021) and Pordata (PORDATA, 2022).

Then, the following sections define the buildings construction standards, the type of use and the type of energy supply for the buildings used in this work.

### 4.1.1 Buildings construction standards

Table 4 shows the number of buildings censored in Portugal and in Lisbon in 2011 depending on the year of construction. As it can been seen, for the case of Lisbon, 64% of the buildings were built before 1960.

**Table 4. Buildings depending on 2011 Census: Total and per construction period (PORDATA - Buildings)**

| | Total | < 1919 | 1919 - 1945 | 1946 - 1960 | 1961 - 1970 | 1971 - 1980 | 1981 - 1990 | 1991 - 2000 | 2001 – 2010 |
|---|---|---|---|---|---|---|---|---|---|
| **Portugal** | 3544389 | 206343 | 305696 | 387340 | 408831 | 588858 | 578845 | 558471 | 510005 |
| **Lisbon** | 52496 | 10279 | 9747 | 13149 | 6965 | 4335 | 2136 | 2922 | 2963 |
| **Portugal** | 100% | 6% | 9% | 11% | 12% | 17% | 16% | 16% | 14% |
| **Lisbon** | 100% | 20% | 19% | 25% | 13% | 8% | 4% | 6% | 6% |

For Madre de Deus neighbourhood, construction standards for buildings are collected from C-TECH project (C-Tech: Climate Driven Technologies for Low Carbon Cities – MIT Portugal). C-TECH aims at researching, developing and pilot-scale a digital smart city platform for urban modelling and planning. The data is achieved in a shapefile format. The shapefile contains reliable information about the geometrical characteristics of the building plans (number of floors above/below ground and height), construction standards and their use-type (single or multi residential, school, commercial).

In Table 5 are gathered the construction standards used in the case studies, depending on the year of construction of the building. According to these different standards, are defined all the assemblies that characterize the transmittance of the building regarding the walls, roofs, floors and windows. The thermal transmittance values considered in each construction standard are also defined in Table 5.

**Table 5. Construction standards description**

| Construction year | Standard description | U wall (W/m2K) |
|---|---|---|
| 1919-1945 | Granite stone, sloped tile roof | 2.49 |
| 1946-1960 | Granite stone and perforated brick, sloped tile roof | 1.33 |
| 1961-1970 | Double perforated brick | 1.11 |
| 1971-1980 | Double perforated brick | 0.987 |
| 1981-1990 | Double perforated brick | 0.987 |
| 2001-2005 | Double perforated brick 6cm | 0.463 |

### 4.1.2 Use types

The consumption pattern in buildings is defined mostly by the building typology. Depending on the type of building and the people living in it, the consumption of energy varies. Therefore, the patterns will be adapted and defined regarding INE databases.

Specifically, to define the consumption patterns for residential buildings in Madre de Deus, data was collected from a shapefile with census information regarding the statistical section unit: Geographic Information Reference Base in 2011, where the last update of data was in 2018. This information is available on the official website of the National Statistics Institute (INE) (INE - Censos 2011 Resultados Definitivos).

To assign the census data to the proper case study buildings, QGIS is used to join the data derived from census in a specific area with the buildings included in it. In Figure 16 the different sections with census information (brown) and the buildings (red) that belong to each section are shown.

**Figure 16. Buildings classified by sections of Portuguese Census. QGIS view**

Through QGIS, buildings are assigned to one census section and with this, the demand profiles are assigned. Regarding the information gathered from census, three different types of residential profiles are defined as in Table 6. Therefore, after having the census data assigned to the buildings, the different residential profiles will be assigned depending on the specific percentage of each type of profile for each census section. Appendix B gathers the data obtained from the Geographic Information Reference Base that is used to assign the buildings profile according to Census data.

**Table 6. Residential profiles**

| Type of profile | Description |
|---|---|
| Retired family | Family with at least one member retired |
| Unemployed family | Family with at least one member unemployed |
| Employed family | Family with all members employed |

Regarding nonresidential uses, in one of the case studies, a school typology is considered. In the case of the school, the consumption profile is characterized for Portuguese schools considering the energy certification (Ministério das Obras Públicas, “O Regulamento dos Sistemas Energéticos de Climatização em Edifícios (RSECE)-Decreto-Lei n.o 79/2006”, Diário da República, no. 4 de Abril, pp. 53 (2416-2468)).

With all this information considered, Figure 17 shows the daily occupation rate for each type of profile considered in the case studies. Occupation profiles for residential buildings are defined according to data form INE and the school buildings occupation is defined in the RSECE mentioned before. As it can be seen, the residential profiles are very similar, with high occupation during nights, but low occupation during daylight hours. For services (school) is the opposite case.

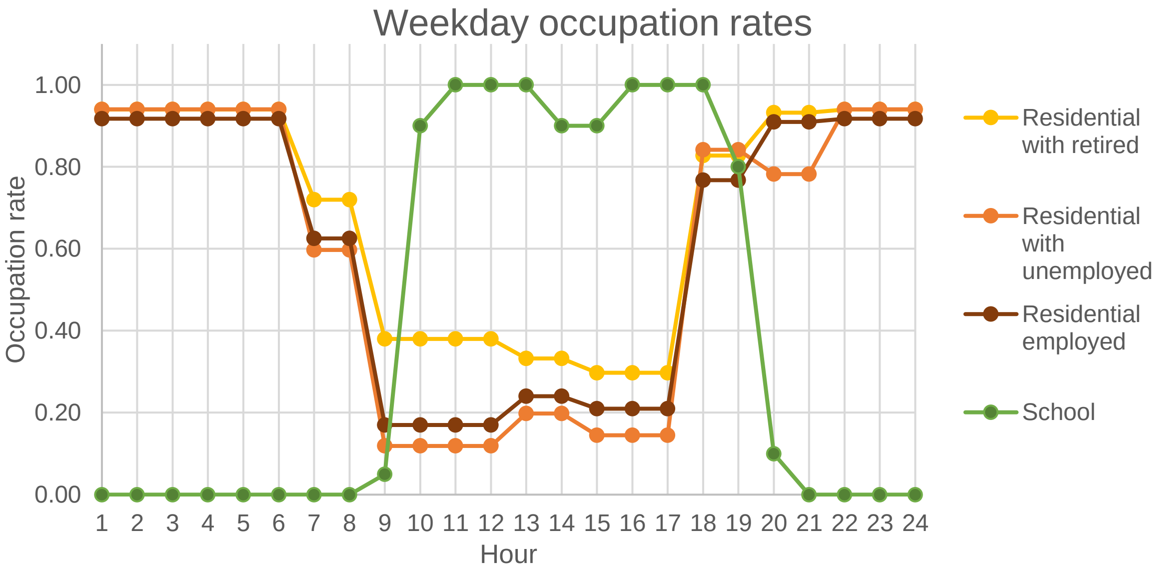


**Figure 17. Weekday occupation rates**

To estimate the number of persons in each building, it is stablished a ratio of m²/person depending on the type of building. Table 7 shows the values used for each building archetype. These values are defined according to C-TECH project and RSECE referred before.

**Table 7. m²/person in each building profile**

| Profile | m²/person |
|---|---|
| Single residential | 35 |
| Multi residential | 22 |
| School | 10 |

Regarding the heating and cooling, for every building typology, the range of temperatures in which heating or cooling system is active is between 21ºC and 26ºC. This means that, when the indoor temperature of the building is below 21ºC, heating is turned on. Also, when indoor temperature gets over 26ºC, cooling system is turned on.

Figure 18 shows the hourly schedule defined in City Energy Analyst for heating and cooling systems based on the occupancies. Value 1 refers to the setpoint of the equipment, while 0 means that it is off.

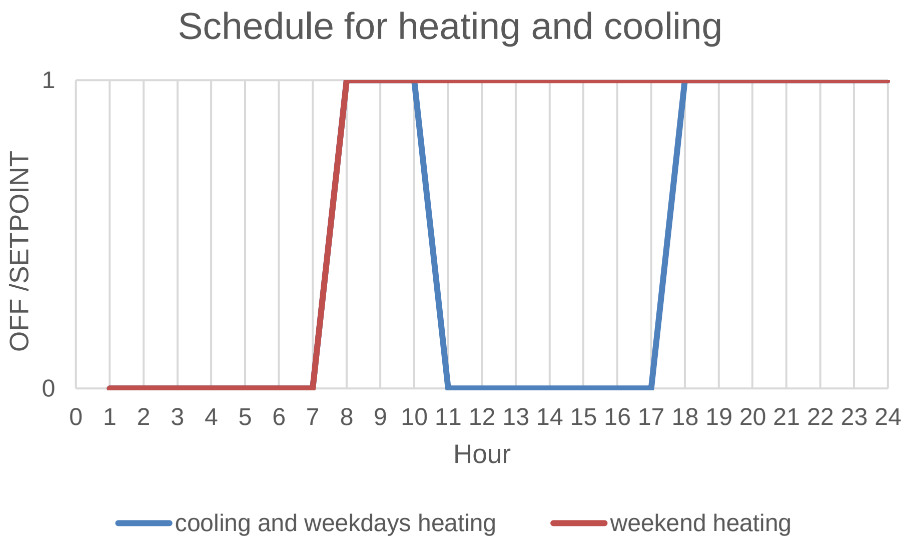


**Figure 18. Setpoint and turned off for cooling and heating systems**

### 4.1.3 Energy supply

Domestic energy consumption is diverse and depends on the energy supply equipment and the usage patterns and occupants' expectations. In order to collect representative data regarding the type of the energy supply in the case study buildings, research has focused on energy agencies and statistics institutions in Portugal.

Figure 19 shows the distribution of energy sources by type of use from INE. The energy consumption for water heating is mainly carried out using equipment with derived from gas source (30% through LPG

Bottle, 13% Piped LPG and 35% Natural Gas). Biomass is the main source of energy used in the heating of the environment (67.1%), but heating diesel also represents an important share of energy consumption in this type of use (12.4%), as well as Electricity (10.0%). (Inquérito ao consumo de energia no sector doméstico: 2020, INE 2021).

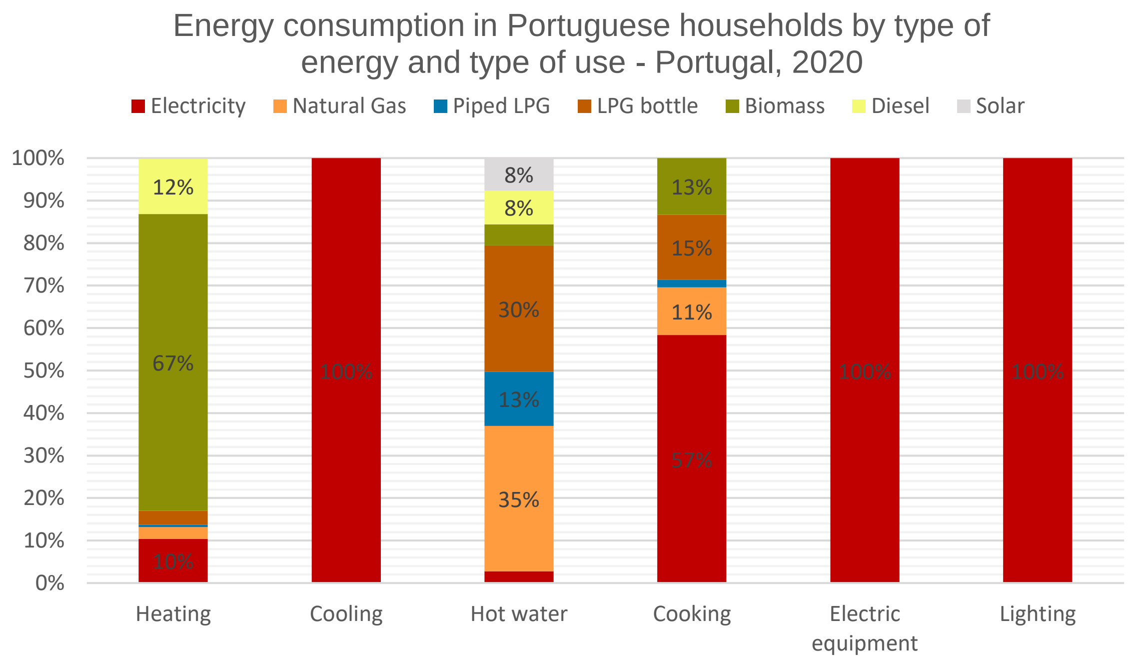


**Figure 19. Type of energy supply by appliance (INE, 2021)**

With the above information taken into account, the following assumptions are done. For the heating of the environment, the biomass as a source is not going to be considered because this source is more typical for rural areas, also fireplaces are not common in Lisbon housing. Then, for the environment heating the two sources considered are electrical and gas. As well as in the reference the gas percentage is higher than the electricity, 60% of the buildings are considered to have gas supply for heating and the 40% are considered to use electricity for heating. Regarding the hot water supply, the main source in this case is the natural gas. Therefore, in the case studies considered in this work, the supply for hot water is natural gas in the 90% of the buildings, and the rest with electricity supply.

Table 8 defines the type of energy supplies and its efficiencies considered for the building energy simulation in City Energy Analyst.

**Table 8. Supply characterisation for case studies**

| Supply | Description | Feedstock | Efficiency |
|---|---|---|---|
| HEATING | Electrical boiler | ELECTRICAL | 0.9 |
| | Natural gas-fired boiler | NATURAL GAS | 0.8 |
| HOT WATER | Electrical boiler | ELECTRICAL | 0.9 |
| | Natural gas-fired boiler | NATURAL GAS | 0.8 |
| COOLING | Heat pump/air-air | ELECTRICAL | 2.7 |
| | None | NONE | - |
| EQUIPMENTS | Consumer energy mix | ELECTRICAL | 0.99 |

## 4.2 PV solar generation characterisation

This section describes all the parameters defined on the case studies regarding the photovoltaic generation. As mentioned in the methodology chapter, the forecasting for the PV generation is made through City Energy Analyst. With the data regarding the location and geometry of the buildings and the meteorological file for Lisbon from Energy Plus (EnergyPlus) the solar radiation for rooftops on each building is calculated.

According to the methodology, in the following sections the parameters considered for the case studies are defined, in order to calculate the photovoltaic production in buildings' roofs.

### 4.2.1 Minimum threshold

According to PV-GIS tool (PVGIS Photovoltaic Geographical Information System), the maximum horizontal annual solar radiation for the city of Lisbon is 1764 kWh/m2. Therefore, in this work a minimum annual threshold of 1000 kWh/m$^2$ for installing PV systems is chosen. This means that, surfaces that receive less radiation, will not be considered as suitable for installing PV panels. Regarding the variability of roofs orientations, this measure will allow to avoid the installation of panels in shaded and not suitable surfaces.

### 4.2.2 Tilt angle

The optimal PV slope angle for Lisbon, according to the PV-GIS tool is 33º. This is the value assumed for the present case studies.

### 4.2.3 Area of roof covered by PV

City Energy Analyst does not consider the inclination of the roofs, treating them as flat surfaces, as it can be seen in Figure 20.

**Figure 20. 3D view for buildings in CEA.**

This was a limitation in order to assess the roof coverage with PV panels since in this area the buildings have gable roofs, as it can be viewed in Google Maps (Madre Deus - Google Maps). The approach to this limitation was to calculate the coverage ratio considering that buildings have gable roofs. Therefore, for each building rooftop area, the area for a 33º gable roof was calculated, as this is the tilt angle considered for the PV panels. Considering that just one of the sides of the roof would be available to have PV panels (the most orientated to the South quadrant) and the borders of the roofs, the roof coverage is defined.

### 4.2.4 PV panels features

The PV panels considered represent a generic monocrystalline panel, with 16% of nominal efficiency. The nominal operation cell temperature is 43.5 ºC with a cell maximum power temperature coefficient of 0.0035 1/ºC.

## 4.3 EC characterisation

As mentioned in the methodology, each building is considered in three different scenarios (building without EC, building in EC, building in EC with CBESS). This way, in this section all the parameters regarding the energy communities for the Portuguese framework and how energy tariffs are applied in these cases are characterised.

### 4.3.1 Portuguese framework

For each building scenario, the framework that regulates the self-consumption is different. ERSE is the Regulatory Entity for Energy Services in Portugal (ERSE - Início) and defines the typology of self-consumption as it is regulated in the country. Table 9 gathers the typology and the different features for each type of self-consumption. Surplus selling is allowed in all the cases. Then, for energy communities the production sharing rate for each building can be established by the participants. In the case of having storage available, also a rate for storage sharing should be defined.

**Table 9. Typology of self-consumption for the different scenarios**

| **Scenario** | **Typology** | **Surplus sale** | **Production sharing** | **Storage sharing** |
|---|---|---|---|---|
| Building without EC | Individual self-consumption | ✓ | ✗ | ✗ |
| Building in EC | Collective self-consumption with public grid use | ✓ | ✓ | ✗ |
| Building in EC with CBESS | Collective self-consumption with storage and public grid use | ✓ | ✓ | ✓ |

### 4.3.2 Tariffs

**The grid tariffs considered were the ones reported by ERSE to the regulated market. For comparison purposes, the base case (without self-consumption), the tariff considered is a simple tariff. Then, for all the other scenarios (building without EC, building in EC and building in EC with CBESS), the tariff considered is a dual-tariff. Table 10 shows the prices of active energy for each scenario. The tariffs considered are the temporary sales rate to end customers in LRT (≤20.7 kVA and >2.3 kVA). The dual-tariff hours are defined in**

Table 11.

**Table 10. Energy costs**

| **Scenario** | **Type of tariffs** | | **EUR/kWh** |
|---|---|---|---|
| Base case | Simple tariff | | 0.1583 |
| All self-consumption scenarios | Dual tariff | off-peak hours | 0.1044 |
| | | peak hours | 0.1917 |

**Table 11. Dual-tariff time periods**

| **Bi-hourly tariff** | **Days** | **Hours** |
|---|---|---|
| Empty hours | Monday to Friday | 0h-7h |
| | Saturday | 0h-9h; 14h-20h; 22h-24h |
| | Sunday | 0h-24h |
| Not empty hours | Monday to Friday | 7h-0h |
| | Saturday | 9h-14h; 20h-22h |
| | Sunday | - |

Regarding the surplus sale, Portuguese regulation establishes that the price for the PV sold electricity to the grid is 90% of the monthly average final price from OMIE (Preço final médio - Consumo nacional | OMIE).

## 4.4 Case studies definition

In this section the characteristics for each case study are described. Figure 21 shows the overview of the buildings studied.

**Figure 21. Case studies overview**

### 4.4.1 Case study A

Case study A considers only single residential buildings. Therefore, in this case 30 single residential buildings are being studied. Table 12 shows the construction standards, energy supply and profiles established for the buildings in case A.

**Table 12. Characterisation of buildings for case study A**

| | N | % of buildings |
|---|---|---|
| **Construction standard** | | |
| 1946 – 1960 | 19 | 63% |
| 1961 – 1970 | 10 | 33% |
| 1981 – 1990 | 1 | 3% |
| **Energy supply** | | |
| Heating (source: GN or ELECT) | 19 / 11 | 66% / 34% |
| Hot water (source: GN or ELECT) | 29 / 1 | 97% - 3% |
| Cooling (source: ELECT or NONE) | 30 / 0 | 100% - 0 |
| Equipment (source: ELECT) | 30 | 100% |
| **Profile** | | |
| Family with retired | 13 | 43% |
| Family with unemployed | 3 | 10% |
| Family with employed | 14 | 47% |

### 4.4.2 Case study B

Case study B considers single and multi-residential buildings. In this case 30 single and multi residential buildings are being studied. Table 13 shows the construction standards, energy supply and profiles established for the buildings in case B.

**Table 13. Characterisation of buildings for case study B**

| | N | % of buildings |
|---|---|---|
| **Building use** | | |
| Single residential | 17 | 57% |
| Multi residential | 13 | 43% |
| **Construction standard** | | |
| 1946 – 1960 | 10 | 33% |
| 1961 – 1970 | 20 | 66% |
| **Energy supply** | | |
| Heating (source: GN or ELECT) | 23 / 7 | 76% / 24% |
| Hot water (source: GN or ELECT) | 30 / 0 | 100% / 0 |
| Cooling (source: ELECT or NONE) | 30 / 0 | 100% / 0 |
| Equipment (source: ELECT) | 30 | 100% |
| **Profile** | | |
| Family with retired | 13 | 43% |
| Family with unemployed | 3 | 10% |
| Family with employed | 14 | 47% |

### 4.4.3 Case study C

Case study C is considering single and multi-residential buildings, and services. Therefore, in this case, a school is included in the case study. Table 14 shows the construction standards, energy supply and profiles established for the buildings in case C.

**Table 14. Characterisation of buildings in case C**

| | N | % of buildings |
|---|---|---|
| **Building use** | | |
| Single residential | 15 | 50% |
| Multi-residential | 10 | 33% |
| School | 5 | 17% |
| **Construction standard** | | |
| 1946 – 1960 | 9 | 30% |
| 1961 – 1970 | 21 | 70% |
| **Energy supply** | | |
| Heating (source: GN or ELECT) | 24 / 6 | 80% / 20% |
| Hot water (source: GN or ELECT) | 30 / 0 | 100% / 0 |
| Cooling (source: ELECT or NONE) | 30 / 0 | 100% / 0 |
| Equipment (source: ELECT) | 30 | 100% |
| **Profile** | | |
| Family with retired | 10 | 33% |
| Family with unemployed | 2 | 7% |
| Family with employed | 12 | 43% |
| School | 5 | 17% |

Having each case study defined, the buildings are simulated in CEA. Then, through the code, the three different scenarios for the self-consumption in buildings are considered (building without EC, building in EC, building in EC with CBESS). For the scenario of building in EC with CBESS, the sizing for the batteries is defined with the capacities appearing in Table 15. The KPIs for each scenario are presented and discussed in chapter 5.

**Table 15. CBESS capacity defined for each case study**

| | CBESS capacity (kWh) |
|---|---|
| Case study A | 550 |
| Case study B | 1240 |
| Case study C | 1260 |

Buildings' profiles and type of energy supply technologies assigned for each case study are presented in Appendix C.

# CHAPTER 5

# 5 RESULTS AND DISCUSSION

This chapter presents the results for the case studies defined above. The aim of this chapter is to discuss the Key Performance Indicators obtained for each case study both at the building and energy community level.

First, in subchapter 5.1 results from UBEM are presented. In subchapter 5.2 the results at a building level for each case study are reported. Also, at the end of this section, there is a highlight of the differences observed for each building typology through the different case studies. In section 5.3 the results are presented at an energy community level, comparing between the different case studies and scenarios considered. Furthermore, section 5.4 shows a sensitivity analysis for CBESS capacity.

## 5.1 UBEM results

In this section the results obtained with City Energy Analyst are presented regarding the demand and PV generation on the different buildings considered in the case studies. Firstly, average yearly demands for each building typology are gathered in Table 16 and the different load profiles are presented in Figure 22 and Figure 23 for a typical summer and winter period.

**Table 16. Electricity demand average results by building typology**

| **Building typology** | **AVG Demand (kWh/year)** | **AVG Occupied area ($m^2$)** | **AVG kWh/$m^2$year** |
|---|---|---|---|
| SINGLE RESIDENTIAL 1946-1960 | 2593 | 107 | 24 |
| SINGLE RESIDENTIAL 1961-1970 (electric heating) | 14381 | 98 | 150 |
| SINGLE RESIDENTIAL 1981-1990 (electric heating) | 14781 | 80 | 185 |
| MULTI RESIDENTIAL | 27991 | 1106 | 25 |
| SCHOOL | 39949 | 1404 | 28 |

As the second and third type of single residential buildings have electric heating, their average and per $m^2$ demands are considerably higher than the typology without electric heating. Moreover, it is important to highlight that indoor comfort settings from UBEM result on higher comfort standards than the ones implemented in reality, and consequently leads to higher energy demands.

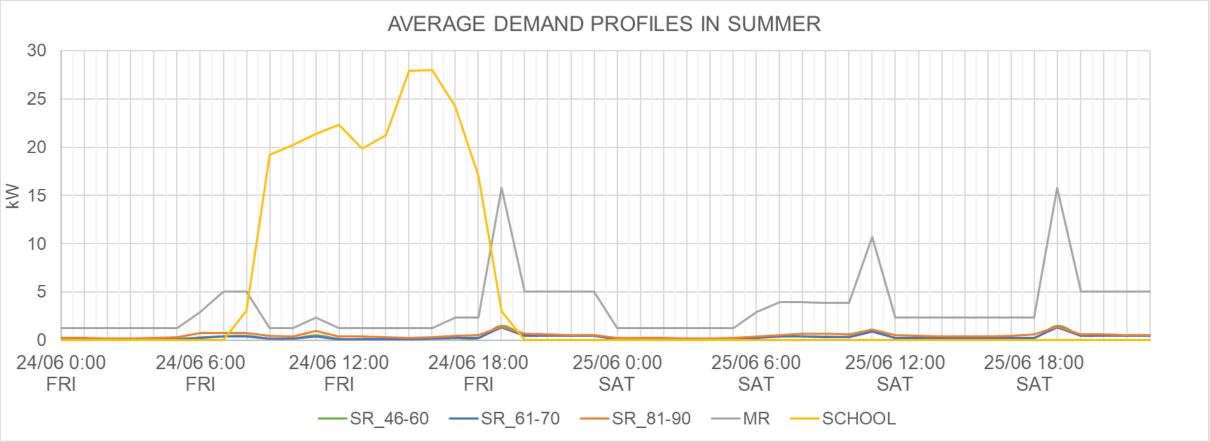


**Figure 22. Average demand profiles in summer for the different building typologies.**

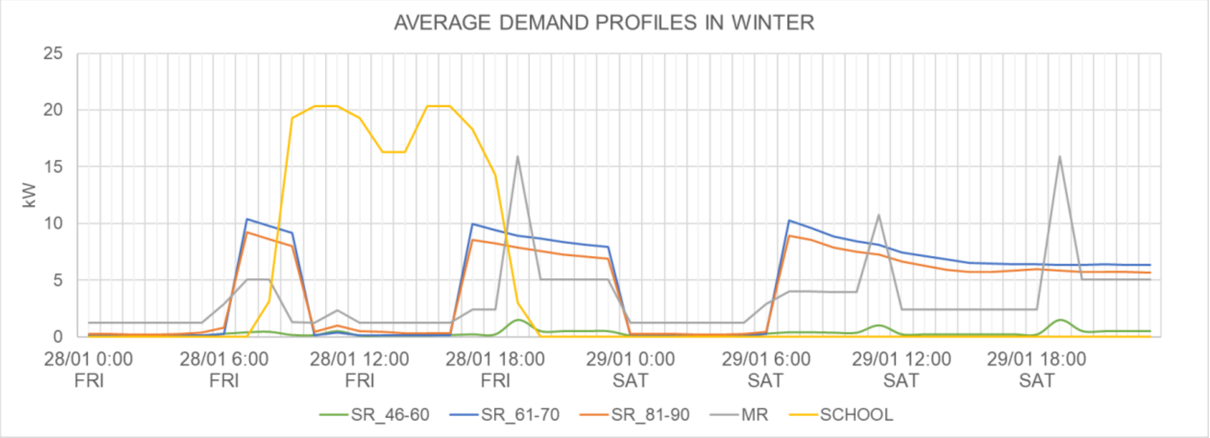


**Figure 23. Average demand profiles in winter for the different building typologies.**

As it can be observed, school has a daylight curve without consumption on weekends and residential buildings have peaks of demand in early hours in the morning and late afternoon hours, following the occupation of the buildings. During the winter period, peak demands in winter for the single residential buildings with electrical heating reach 10 kW. As mentioned before, these peaks are high due to the comfort standards defined in CEA.

Regarding now the PV generation, Table 17 shows the average of PV capacity installed in roofs and the yearly generation for each building typology.

**Table 17. Average PV generation results by building typology**

| Building typology | AVG PV installed (kWp) | AVG Roof area ($m^2$) | AVG PV Generation (kWh/year) | AVG kWh/$m^2$ of floor area |
|---|---|---|---|---|
| SINGLE RESIDENTIAL 1946-1960 | 3.8 | 60.7 | 3283 | 30.0 |
| SINGLE RESIDENTIAL 1961-1970 | 3.8 | 58.8 | 3183 | 32.4 |
| SINGLE RESIDENTIAL 1981-1990 | 2.9 | 48.6 | 2636 | 33.0 |
| MULTI RESIDENTIAL 1961-1970 | 11.7 | 192.7 | 10395 | 9.4 |
| SCHOOL | 48.0 | 792.3 | 42898 | 33.2 |

Table 18 shows the total energy demand and PV generation values obtained in each case study. Demand and generation increase in each case due to the addition of multi residential buildings for case B, and due to the school buildings for case C.

**Table 18. Total demand and PV generation in EC**

| Case study | Demand (kWh/year) | PV generation (kWh/year) | PV installed (kWp) | Roofs area ($m^2$) |
|---|---|---|---|---|
| Case A | 201351 | 93582 | 104.7 | 1729.4 |
| Case B | 486798 | 189572 | 212.7 | 3511.6 |
| Case C | 595989 | 369266 | 413.6 | 6828.5 |

## 5.2 Building level results

In this chapter the results at a building level for the different buildings' typologies in each case study are presented. Graphs show the average yearly electricity demand for each building typology and the electricity demand supply for each scenario considered in this work:

- SC1: Building without EC
- SC2: Building in EC
- SC3: Building in EC with CBESS

Thus, in Figure 24Figure 25 Figure 26 for each scenario it is shown the percentage of the demand covered by the grid (blue), self-consumed in the building (yellow), local electricity from the sharing of PV surpluses (green) and the electricity that comes from the community battery storage system (CBESS) (purple).

Moreover, the following graphs also show the average self-consumption (SC) and self-sufficiency (SS) rate for each building typology. Self-sufficiency, presented as a black spot, will change depending on the scenario considered (SC1, SC2 or SC3) because in each case, the electricity demanded from the grid will be different. Regarding the self-consumption, as it is referred to the building surpluses and its PV production, will not vary within the different scenarios considered.

At the end of this section, in 5.1.4, the results obtained for each building typology are compared among case studies.

### 5.2.1 Case study A

Figure 24 shows the results for the case study A. Here, the three different type of building typologies considered are: Single residential 1946-1960, single residential 1961-1970 with electric heating and single residential 1970-1980 with electric heating and hot water.

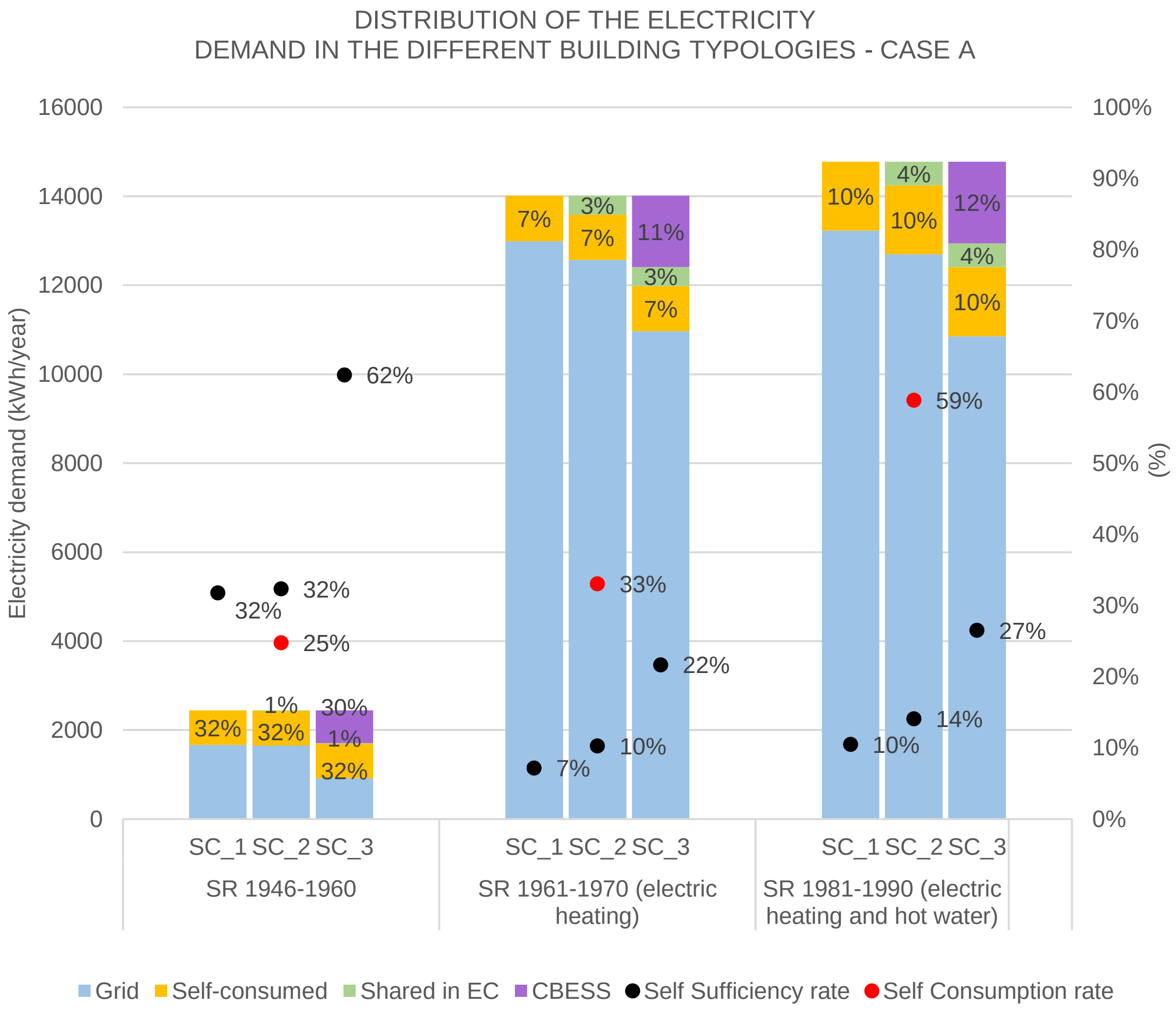


**Figure 24. Case A. Distribution of the electricity demand, self-sufficiency and self-consumption rates**

Regarding the first typology of buildings presented, SR 1946-1960, the average demand is 2400 kWh/year, just considering electrical appliances and lighting. For these buildings, the demand covered with the generation from panels on roofs is on average 32%. Then, considering the buildings in an EC, the direct surpluses shared in the EC represent 0.7% of the demand, and when considering the CBESS, the coverage from the storage system is the 30% of the total demand. Therefore, the self-sufficiency rates obtained for SR 19646-1960 buildings in each scenario are 32%, 32% and 62% respectively. Self-consumption rate is 25%.

Single residential buildings from 1961-1970 have on average demand of 14000 kWh/year. In this case, the electrical demand includes heating and cooling supply. It is important to remark that this value considers achieving the thermal comfort in the building, which does not fit with the Portuguese reality due to several factors such as low penetration of HVAC systems and energy poverty, as mentioned in (Palma, Gouveia and Simoes, 2019). In this case, the demand covered by the PV represents 7%. Then, 3% of the demand is covered by sharing surpluses among the energy community, when considering the building in an EC and when considering CBESS, the demand covered by the storage system is 11%. Self-sufficiency rates obtained are 7%, 10% and 22% respectively for each scenario. Self-consumption rate is 33%.

The third typology of single residential buildings analysed were built during 1981-1990 and this typology considers the existence of electric heating and hot water supply. The electricity demand is on average 14800 kWh/year. In this case, the demand covered by PV generation on roofs represents 10%. When considering the building in an EC, 4% of the demand is covered with PV surplus sharing and the 12% covered by batteries when considering the CBESS. Self-sufficiency rates are 10%, 14% and 27% respectively for each scenario. Self-consumption rate is 59% in this case.

Therefore, in this case study, the building typology with highest self-sufficiency values is the single residential built between 1946-1960 (SR 1946-1960). The three building typologies have similar daily curves, as they are all residential. Nevertheless, as this typology has lower demand, the coverage with self-consumption on roofs will be higher, leading to higher self-sufficiency rates.

Regarding the surpluses sharing in the EC, second and third typology are more benefited by this sharing than the first one. As it can be seen, the first typology is the one with more surpluses (75%). This indicates that the sharing surpluses received by the second and third typology, comes from the surpluses in the first one.

As it is expected, the incorporation of the CBESS in the EC leads to all typologies to higher self-sufficiency rates. The third one will be the one that gets more kWh from the CBESS (the 12% of 14800kWh), as the allocation of the energy available in CBESS is proportional to the building demand in each timestep, and this third typology is the one with more demand.

### 5.2.2 Case study B

Figure 25 presents the results at a building level for the case study B. Here, the different building typologies considered are: Single residential 1946-1960, single residential 1961-1970 with electric heating and multi-residential 1961-1970. In comparison with the case A, now multi residential buildings are evaluated.

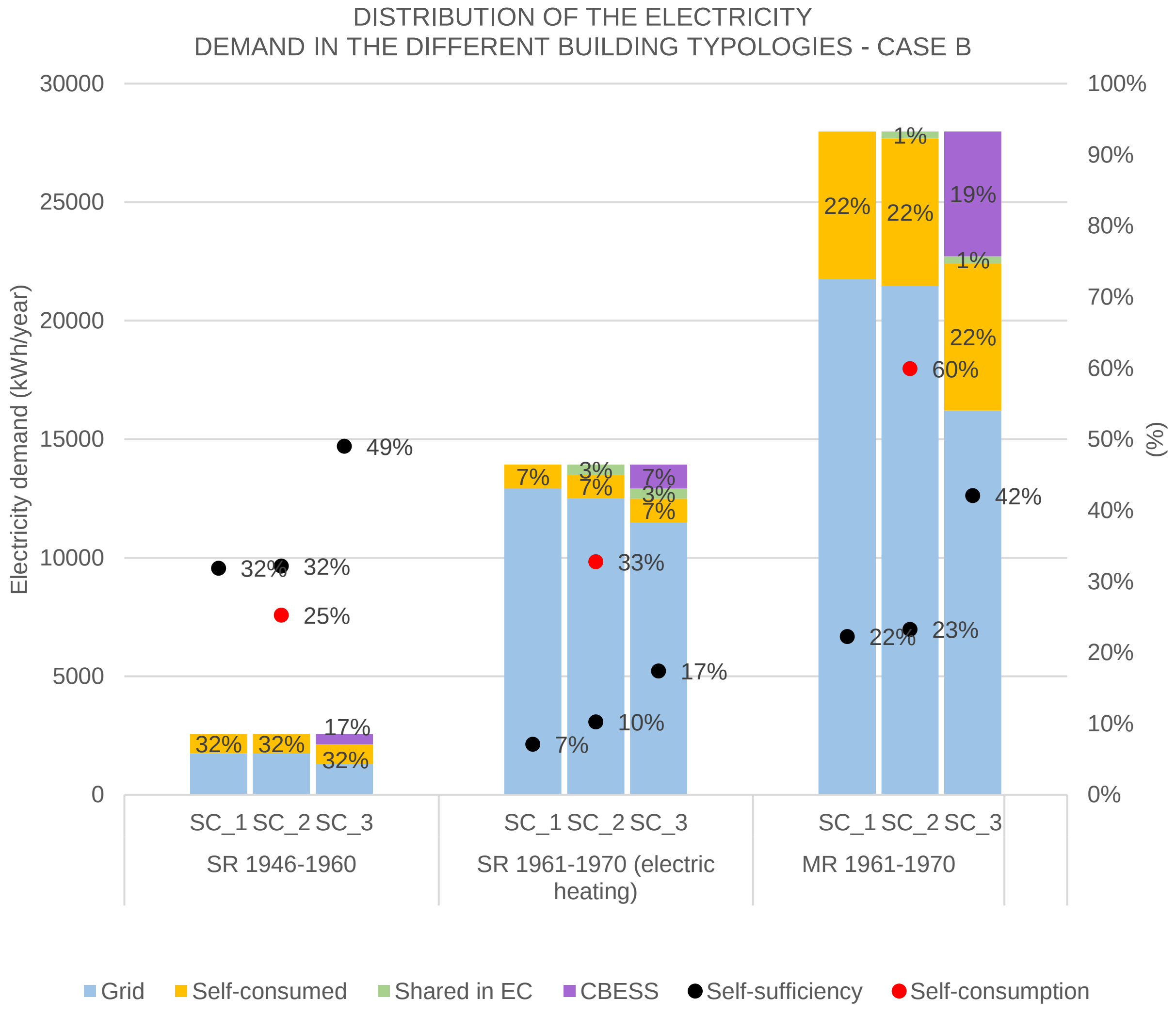


**Figure 25. Case B. Distribution of the electricity demand, self-sufficiency and self-consumption rates**

For the multi residential buildings, the average demand is 28000 kWh/year and has an indicator of 25 kWh/m². In this case, 22% of the demand is covered by PV generation in roofs, 1% is covered by the surpluses sharing and when considering CBESS, 19% of the demand is covered by the storage system. Therefore, self-sufficiency rates for each scenario considered are 22%, 23% and 42% respectively. Self-consumption rate for these buildings is 60%.

As the first and second typology considered are the same as in the case study A, results are also equal except for the third scenario (SC_3). In this case study, the self-sufficiency in the third scenario for these typologies are 49% and 17%, respectively.

Regarding the surpluses shared in the EC, as all the buildings typologies are residential and have similar demand curves, hence, sharing percentages are expected to be low. We could expect that multi-residential buildings would benefit more from the PV surplus shared within the community, which however is not true, and could be explained by the low match of load demand and solar generation curve. Nevertheless, on the scenario with CBESS we see an overall increase of self-sufficiency rate due to the flexibility of the battery to store PV generated electricity.

### 5.2.3 Case study C

Figure 26 shows the results at building level for case study C. The different typologies evaluated now are: single residential 1946-1960, single residential 1961-1970 with electric heating, multi-residential 1961-1970 and school.

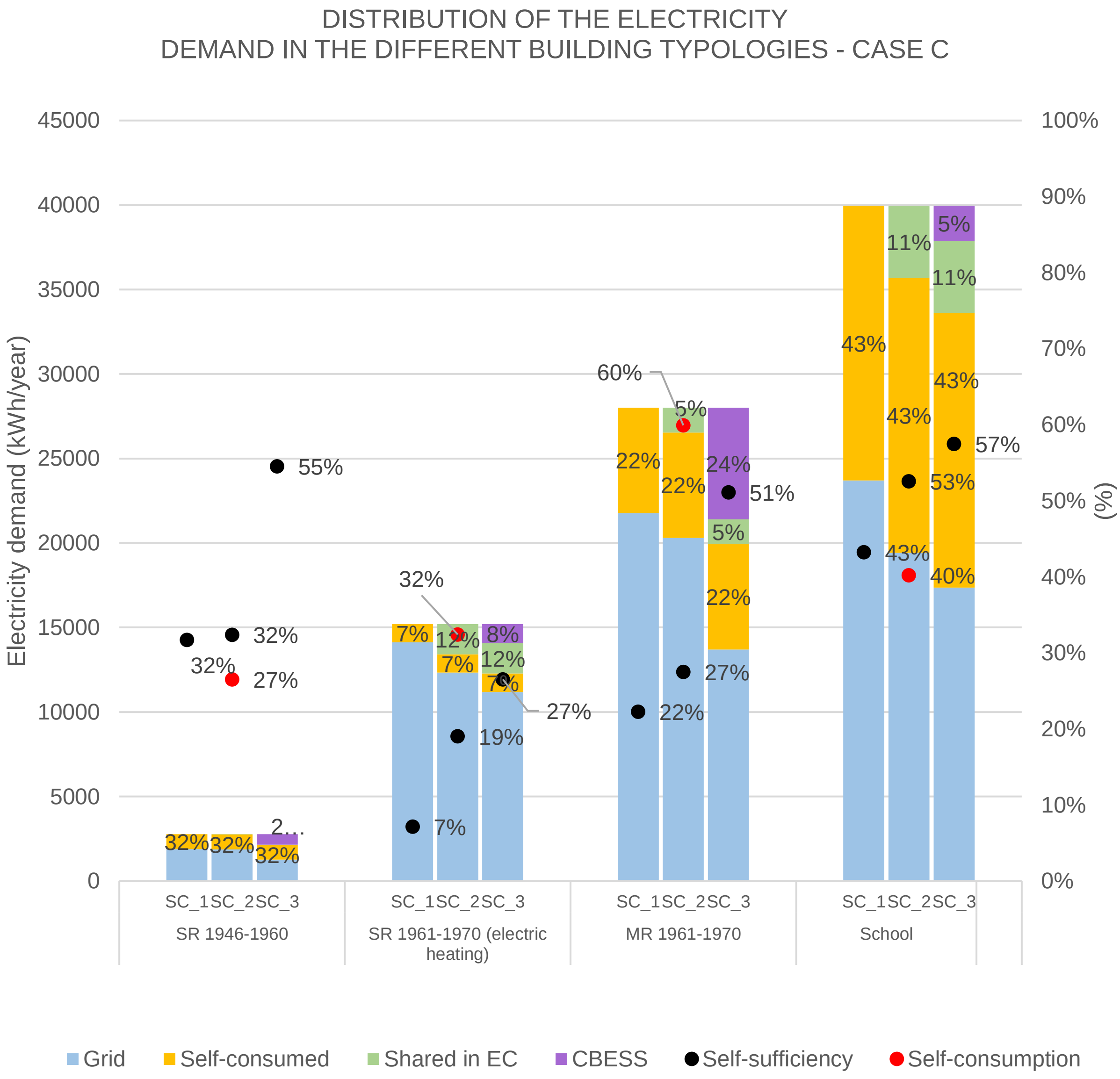


**Figure 26. Case C. Distribution of the electricity demand, self-sufficiency and self-consumption rates**

School buildings have an average demand of 40000 kWh/year. In this case, the demand covered by the PV generation in the building's roofs is 44%. As the demand curve for the school is high during sunlight hours it achieves a higher self-consumption coverage. Also, this typology is the most benefited by the surpluses sharing (11%). This is due to the residential buildings having lower demands during daylight hours, when schools have highest demands, so surpluses in the EC will be allocated in school buildings. Self-sufficiency rates for school buildings in each scenario are 44%, 53% and 57% respectively, while the self-consumption rate is 40%.

Regarding the other building typologies, it can be seen how in scenarios considering buildings in EC (SC_2 and SC_3), the second and third typology (SR with electric heating and MR) have percentages of demand covered by surpluses sharing of 12% and 5% respectively. When analysing scenario 3 (EC with CBESS), the demand covered by the storage system is for each building typology 22%, 8%, 24% and 5%, respectively. Given that for schools there is a higher match between load demand and PV generation, the CBESS will not have such a determinant role as in other typologies.

The percentages of surpluses sharing now have increased. This is because demand curves for residential buildings and school use differ a lot. Therefore, surpluses will be allocated from one building typology to another.

### 5.2.4 Influence of the case studies for the different building typologies

Here are highlighted the main differences observed in the building typology's results depending on the case study considered.

For Single Residential 1946-1960 buildings, differences appear in the third scenario (SC_3), when considering buildings in an EC with CBESS. For this building typology, the demand covered by the CBESS is 33%, 17% and 22% respectively for each case study. For cases B and C, as multi residential buildings have higher demands, are being more benefitted by the storage system, leading to single residential typologies to lower percentages of CBESS coverage comparing to the case A. Therefore, for this typology, the highest self-sufficiency rate is for the case study A (62%).

For Single Residential 1961-1970 with electric heating, differences arise on the percentages of sharing and in the CBESS coverage. Regarding the surpluses sharing, the percentage increases from 3% for cases A and B, to the 12% for case study C. This increase is due to the inclusion of school buildings in the EC. As schools do not have demand during weekends and neither during vacations, all the PV generation in schools is allocated to the residential buildings. Regarding the CBESS coverage, the percentages are 11%, 7% and 8%, respectively. As mentioned before, the addition of the multi residential buildings in case B and 3 lead to lower CBESS coverages.

In Multi-Residential buildings there are also different results for case B and case C. As in the case B percentage of sharing is 1%, this percentage increases until 5% when introducing the school buildings in the EC for the case C, due to the same reason mentioned above. Regarding the percentage of CBESS coverage, it increases from 19% to 24% respectively. In this case, multi residential buildings are more benefited by CBESS when adding school buildings.

Therefore, the building typology that benefits more of being part of an EC without CBESS (SC_2) is the single residential 1961-1970 with electric heating, which has the highest SS increase (12%) when sharing surpluses. Also, in this scenario the school buildings achieve an increase of 10% of the self-sufficiency by benefiting from surpluses in the residential buildings.

Nevertheless, for the scenario with CBESS, the typology with the highest increasement of SS is the multi residential. Also, it is observed that case C is the one with best rates of surpluses sharing, due to the different and not time coincident profiles of demand included in the EC.

## 5.3 Energy community level results

This section analyses the results of the three case studies at an energy community level. The two configurations considered in the framework of energy communities are: collective self-consumption with public grid use (scenario 2) and collective self-consumption with storage and public grid use (scenario 3). The energy Key Performance Indicators are presented and discussed at the end of this section. 5.3.1 and 5.3.2 presents the consumption and PV generation profiles for a summer and a winter week in the energy community for each case study.

### 5.3.1 Scenario 2. Energy community without storage system

Figure 27 and Figure 28 present the load and generation curves for a summer and a winter week in the EC for the case A. As it can be seen, for a typical summer week, the daily PV generation has peaks of 60kWh and covers the demand for daylight hours and still there are high rates of surpluses. The demand curve has peaks of 40 kW. Consumption from the grid only appears when there is no PV generation. For the winter week, the demand profile has higher values. This increase compared with the summer week is due to the electric heating loads and the type of equipment (electrical boiler with 0.9 efficiency). The PV generation peaks in this case are around 20kW, so they still cover the daylight demand peaks of 15 kW.

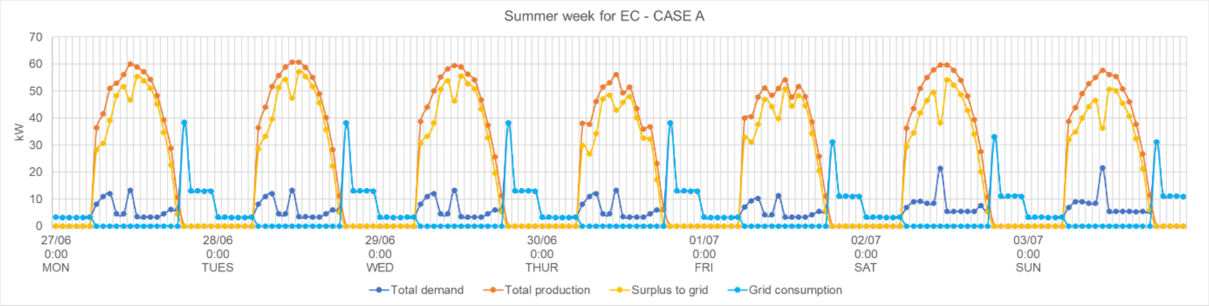


Figure 27. Generation and demand curves in EC during a summer week. Case A

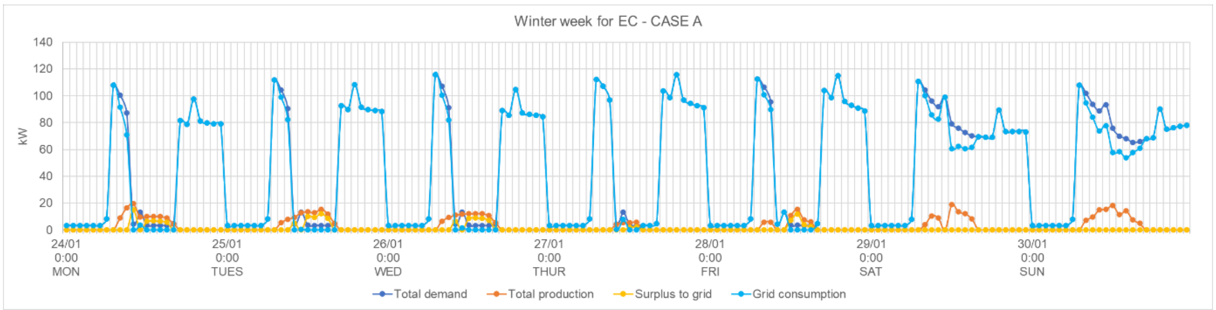


**Figure 28. Demand and generation curves in EC during a winter week. Case A**

Figure 29 and Figure 30 show a typical summer and a winter week for the EC defined in case B. For the summer week, the PV generation has peaks of 125 kW and covers the demand during daylight hours. Demand curve has peaks of 250 kW and the grid consumption occurs when there is not PV generation. During the winter week, demand curves have higher peaks (275 kW) due to the electric heating loads. PV peaks now are around 40 kW and it can be seen how in this case, the generation does not cover all the daily demand.

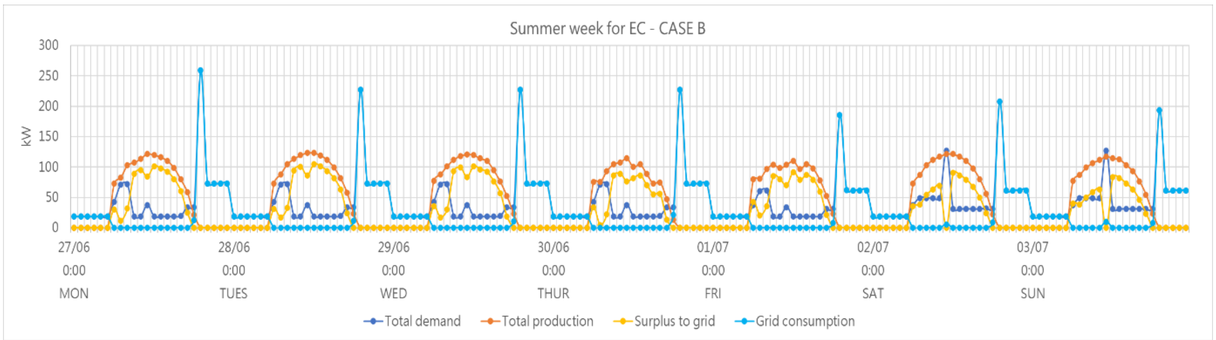


**Figure 29. Consumption and generation curves in EC during a summer week. Case B**

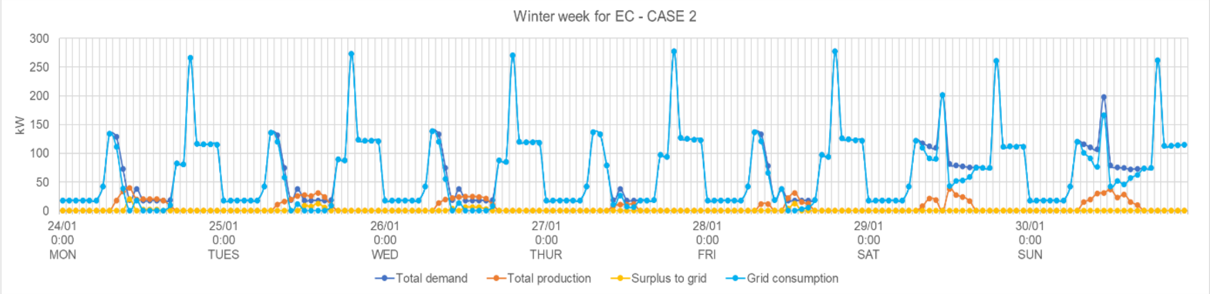


**Figure 30. Consumption and generation curves in EC for a winter week. Case B**

Figure 31 and Figure 32 show a typical summer week and a winter week for the EC defined in case study C. Now, it can be seen how the daily demand curve is different, due to the mix of residential and school uses, except for the weekend, where consumption in only residential. During the summer week, peaks of PV generation achieve 240 kW and cover the electricity demand during sunlight hours. Then, demand peaks from residential buildings at the evening are covered with grid supply.

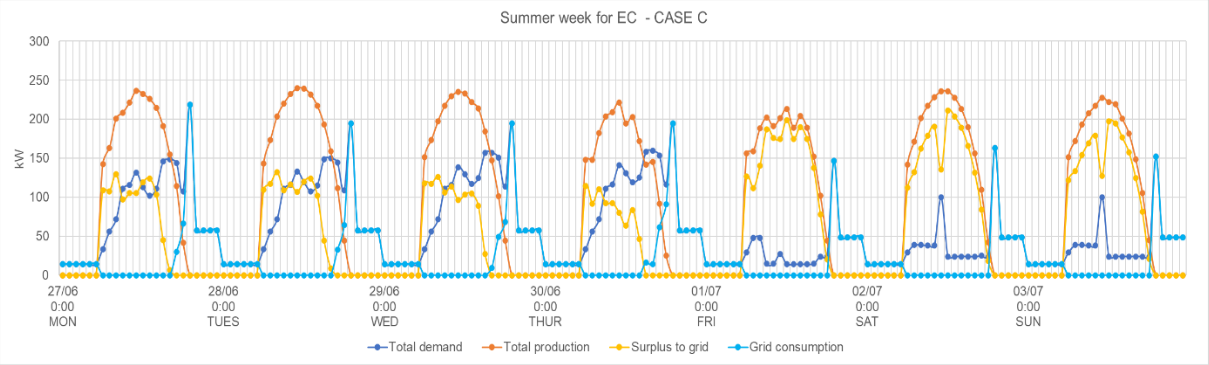


**Figure 31. Consumption and generation curves in EC for a summer week. Case C**

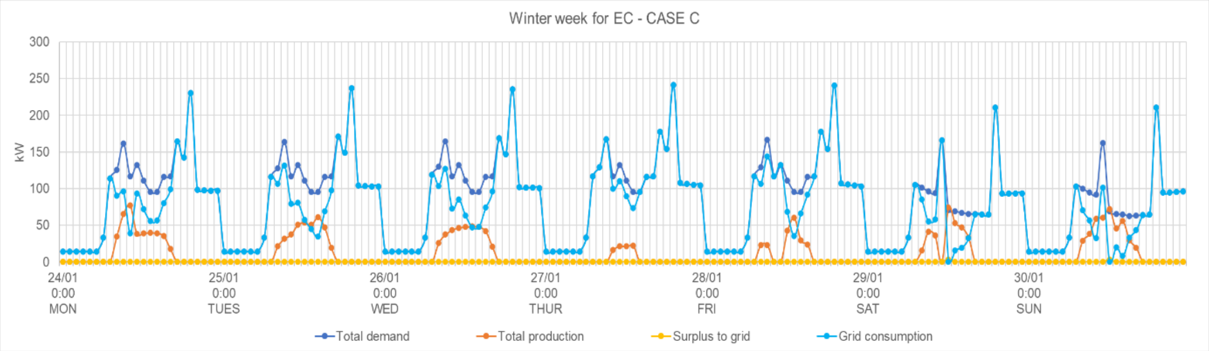


**Figure 32. Consumption and generation curves for a winter week. Case C**

### 5.3.2 Scenario 3. Energy community with central battery storage system

The graphs below illustrate typical summer and winter weeks in the EC when considering the CBESS. Apart from the demand and generation curves, the State of Charge of the CBESS is presented in grey and the maximum and minimum SOC levels are indicated in graphs. This way, the behavior of the CBESS in each case can be analysed.

For this scenario, due to the integration of the CBESS, surpluses to the grid and grid consumption change compared to the scenario 2. As it can be seen in the Figures below, for the studied summer weeks, there is no grid consumption, since CBESS never reaches the minimum level of storage, and thus the battery is always used when there is demand that is not being covered by PV surplus sharing. Surpluses to the grid will appear when the storage system reaches the maximum level. In winter, the CBESS performance is similar for all case studies, with little PV surplus to charge the battery and thus presenting a higher dependency on grid imports.

Figure 33 and Figure 34 show a typical summer and winter week for the EC for the case study A. During summer, as the daily generation is much higher than the demand during nights, the SOC for the CBESS maintain high levels. This leads to low surpluses after charging the battery which influences the EC self-consumption rates. During winter week, CBESS is maintained in minimum levels due to the low PV generation.

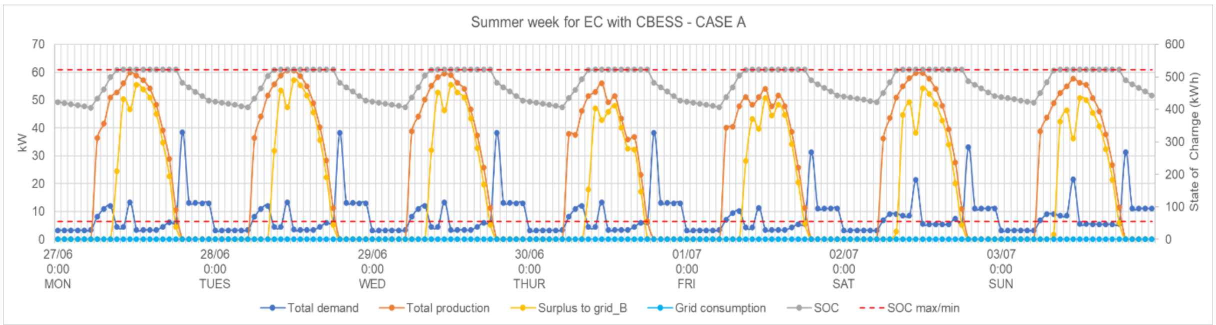


**Figure 33. Demand and generation curves with CBESS for a summer week. Case A**

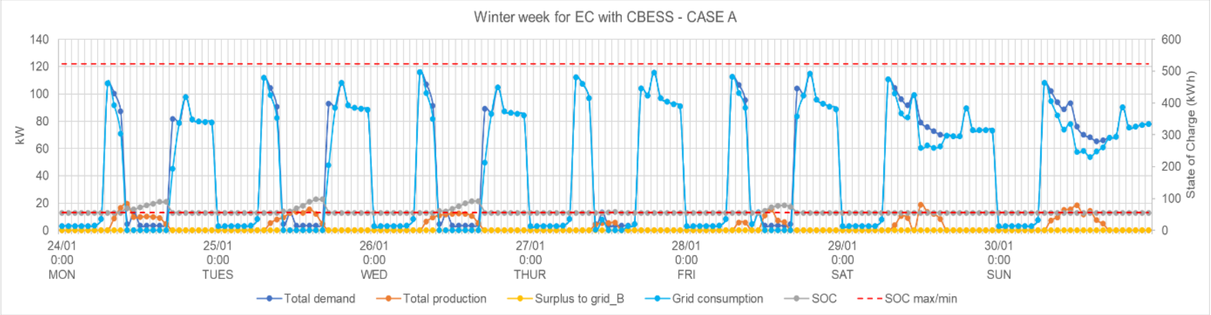


**Figure 34. Demand and generation curves with CBESS for a winter week. Case A**

Figure 35 and Figure 36 show a typical summer and winter week for the EC in the case study B. During summer, in this case, CBESS has daily cycles without reaching the maximum neither the minimum SOC. In the winter week, the CBESS maintains in the minimum level of charge.

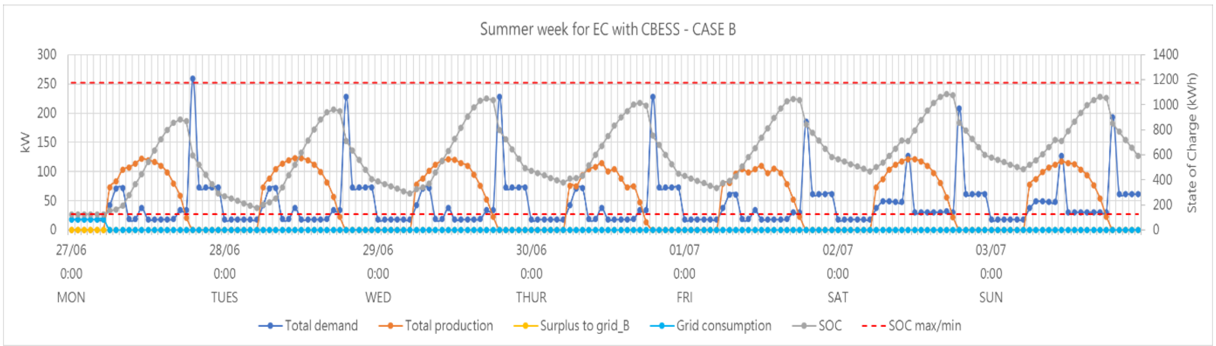


**Figure 35. Demand and generation curves with CBESS for a summer week. Case B**

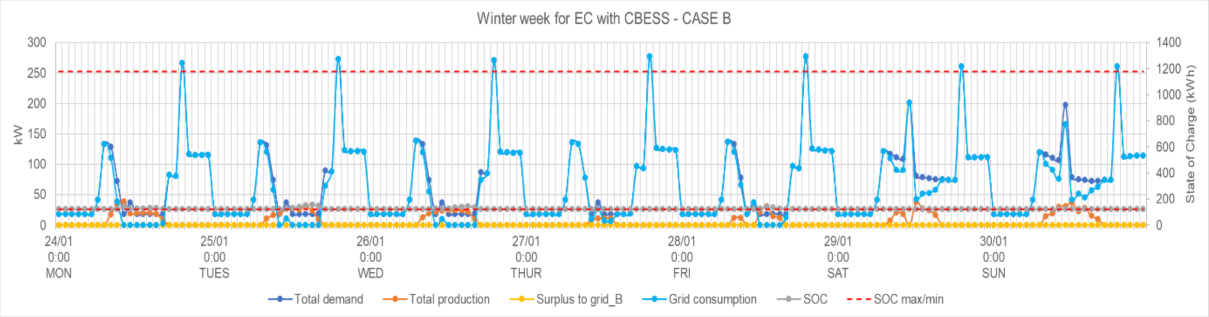


Figure 36. Demand and generation curves with CBESS for a winter week. Case B

Figure 37 and Figure 38 show a typical summer and winter week for the EC in case study C. During summer, it can be observed that surpluses are higher when the school is closed (right part of the figure), due to the lower self-consumption during those days, that would lead the CBESS to reach the maximum level earlier, when compared with the rest of the days. For the winter week, CBESS is maintained in the minimum level. The PV generation is self-consumed by the EC without the use of the storage system.

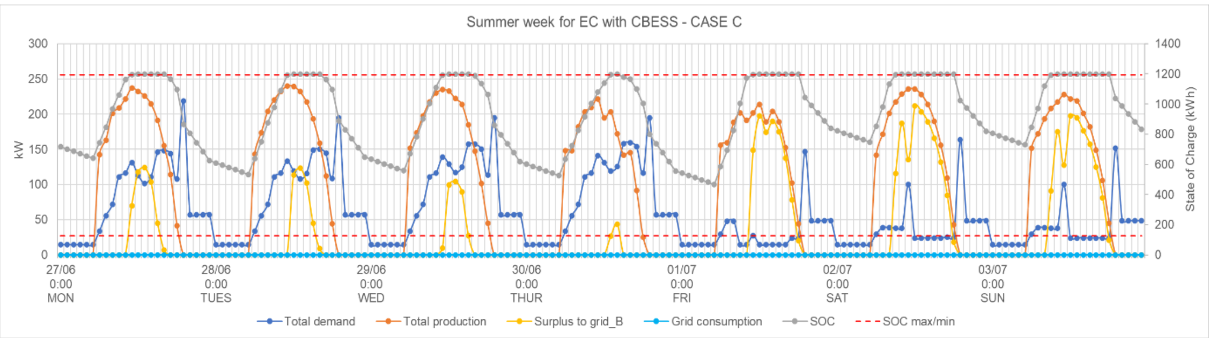


Figure 37. Demand and generation curves with CBESS for a summer week. Case C

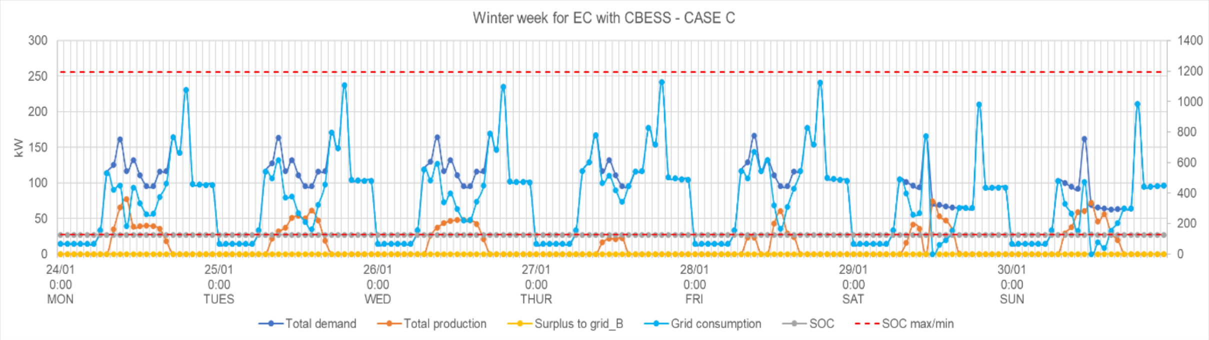


Figure 38. Demand and generation curves with CBESS for a winter week. Case C

### 5.3.3 Self-consumption and self-sufficiency results

Figure 39 gathers the energy Key Performance Indicators obtained for each case study. Results are presented for the two different scenarios considered in energy communities: collective self-consumption with public grid use (scenario 2) and collective self-consumption with storage and public grid use (scenario 3).

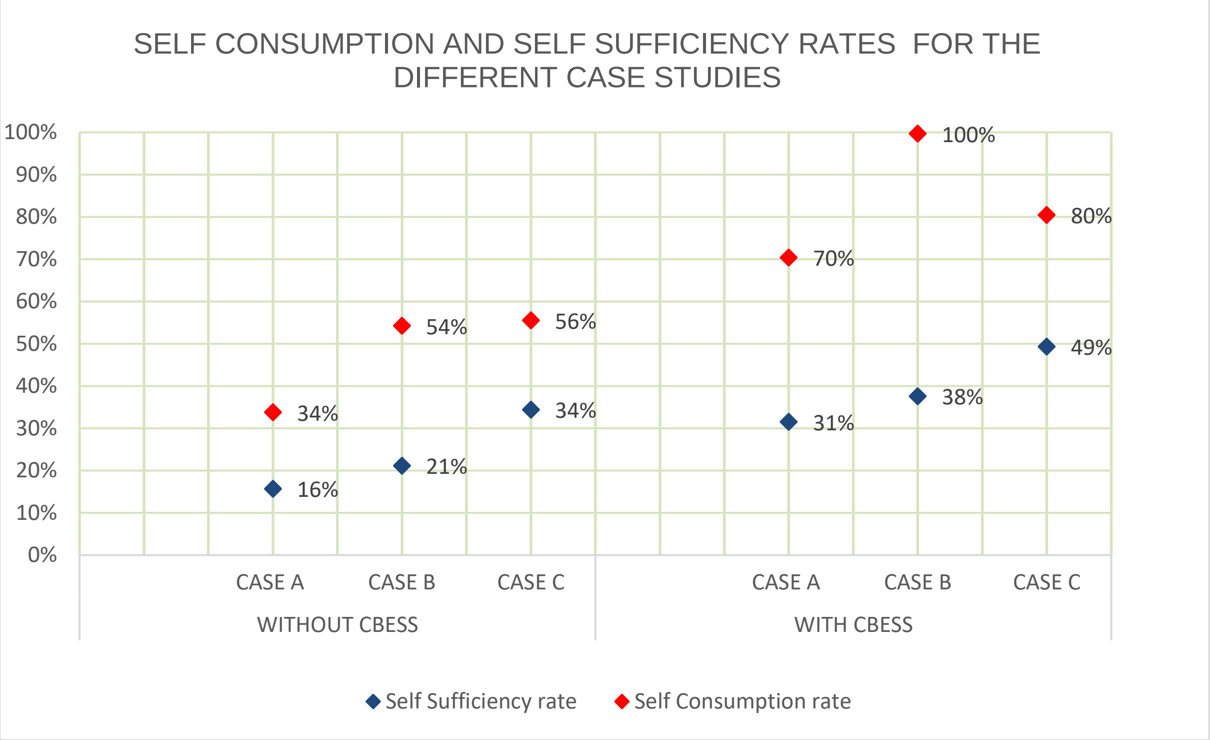


**Figure 39. Self-consumption and self-sufficiency in case studies**

Regarding Scenario 2, self-sufficiencies achieved are 16%, 21% and 34%, respectively for each case study. Having seen the weekly curves in 5.2.1, case C is the one with a higher percentage of demand during the daylight hours, as its curve it is a combination between residential and school use. Hence, this leads to a higher self-sufficiency rate. Regarding the self-consumption, percentages obtained for each case study are 34%, 54% and 56% respectively. Also, as seen in curves from 5.2.1, case A is the one with more percentage of surpluses compared to other cases. Therefore, its self-consumption is the lowest due to the high rate of surpluses.

Regarding the other scenario, when considering CBESS in the EC, self-sufficiencies observed are 31%, 38% and 49%. Self-consumption rates observed increase for each case study until 70%, 100% and 80% respectively. As mentioned in the Methodology, the CBESS is dimensioned to cover the daily average consumption from the grid of the energy community. Besides, as the CBESS is charged with the EC surplus and discharged with the EC demand, the behavior of the system for each case study will vary depending on how this charge and discharge are given. Evolution of the CBESS in each case study can be seen and better understood in the graphs from 5.2.2, during the summer weeks.

These results lead to indicate that for case B, the CBESS does not reach the maximum level (no surpluses to the grid) and rates of charge and discharge are equilibrated, that is why a 100% of self-consumption is achieved in this case.

Comparing both scenarios, it is showed that for all cases the self-sufficiency increases between 15-17% when adding the storage, being the highest increase (17%) for the case study B. Regarding the self-consumption, the average of increase is 35%, having the highest value in the case study B with 46% of increase when adding the storage.

### 5.3.4 Results comparison with literature review

When comparing EC results with literature review, similarities are found in (Pontes Luz and e Silva, 2021) where values of Self-sufficiency of 31% are achieved in a small Portuguese city. Nevertheless, results differ from the ones found in (Syed, Hansen and Morrison, 2020) with 75% of self-sufficiency with storage, while in the present work the self-sufficiency with storage is between 31%-49%.

Regarding the Self-consumption results, in (Luthander *et al.*, 2016) percentages between 43-58% of self-consumption in EC with residential configuration are achieved, that are aligned with the results found on case A and 2, with 34% and 54% self-consumption percentages without storage system. Also, when considering shared storage, self-consumption in (Luthander *et al.*, 2016) increases until 72%, as in case A in this work (70%).

When comparing the differences between scenarios 2 and 3 (without or with CBESS storage), results on Luthander et al. (2015) show that the self-consumption increases by 13–24 percentual points with a battery storage capacity, while in the present work it varies from 36-46%.

In (Reis *et al.*, 2019) an increase of the average self-consumption from 50 to 80% is found, for the case of 10 residential households, with battery storage.

### 5.3.5 GHG emissions

Table 19 shows the results for the $CO_2$ emissions avoided to the atmosphere. Case C is the one with higher levels of emissions avoidance, due to is also the one with the highest demand and generation values. It can be observed the high increase in emissions avoidance when going from the scenario without CBESS to the one with storage, in all case studies.

**Table 19. $CO_2$ emissions avoided in EC**

| | **$CO_2$ emissions avoided ($kgCO_2$/year)** | | |
|---|---|---|---|
| | **Case A** | **Case B** | **Case C** |
| Without CBESS | 7605 | 27797 | 49335 |
| With CBESS | 15265 | 49479 | 70715 |

## 5.4 CBESS analysis

Regarding the differences found in the indicators when applying the same CBESS sizing criteria for all case studies, an analysis has been made to try to explain how the size of the storage system affects the self-sufficiency and self-consumption of the EC. Hence, Figure 40 shows the self-consumption (SC), self-sufficiency (SS) and the average SOC (ASOC) for different capacities of the CBESS. The CBESS sizing criteria studied were:

- covering the 50% of the daily demand from the grid (0.5 DD);
- covering the daily demand from the grid (DD) (used in the case studies); and,
- covering two days of demand from the grid (2 DD).

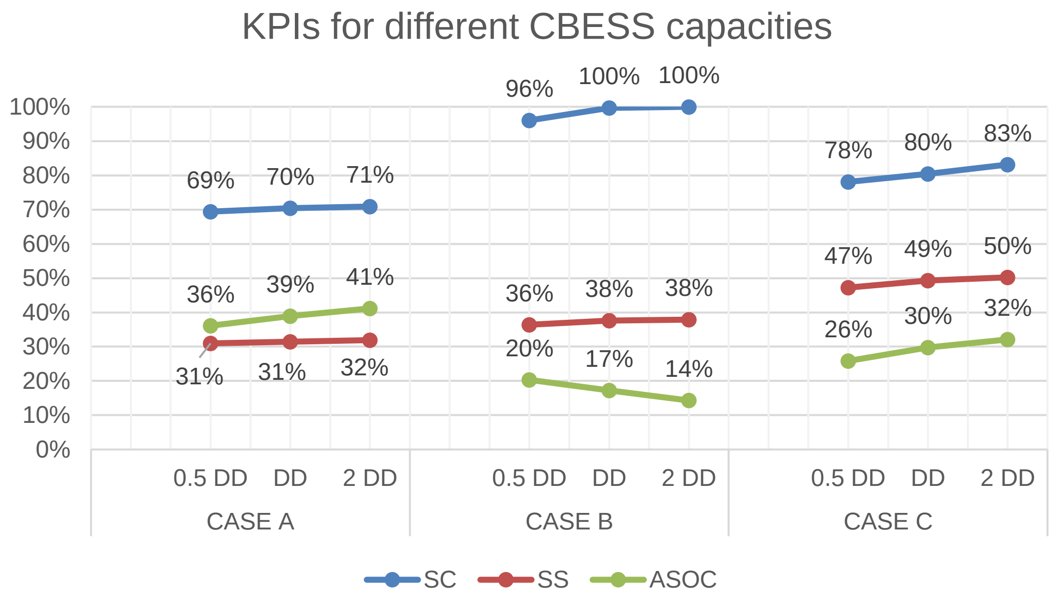


**Figure 40. Self-consumption, self-sufficiency and average SOC for different CBESS capacities**

As it can be observed, although using the same sizing criteria results differ depending for each case study. For the DD sizing, while in case A the self-consumption obtained is 70%, for case B is the 100% and 80% in case C. These values can be better understood by observing the figures in 5.2.2 that show the performance of the CBESS for each case study. In case study A, the CBESS reaches every day the maximum SOC due to the high rates of charge compared to the discharge. This leads to the CBESS to have surpluses to the grid every day, reducing the self-consumption. Nevertheless, in case study B, as daily generation and demand are more equilibrated, CBESS does not reach either the maximum or minimum level, achieving a 100% of self-consumption. By observing the figure from case C study, charge rates are higher than discharge and surpluses to grid also appear as the CBESS reaches the maximum level.

Regarding the different sizing methods studied, it is expected that by increasing the capacity of storage, self-consumption increases. Nevertheless, depending on the case, this increment is different. For instance, when changing from 0.5 DD to DD, the self-consumption increases in 1%, 4% and 3%, respectively for each case study.

These results regarding the self-consumption led to conclude that what more influences on the final value is the relation between daily generation and demand curve. As closer are these parameters, more equilibrated will be the charge and discharge of the CBESS and less surpluses will be injected to the grid. Therefore, in terms of battery operation, the best case is B.

Self-sufficiency values also increase while increasing the CBESS capacity, as more demand will be covered by PV generation. The evolution of the average SOC is also different depending on the case. As seen in figures from 5.2.2, in winter the CBESS is maintained in at minimum SOC level due to the lack of generation, that is the reason why the ASOC is low in every case.

## 5.5 Economic results and analysis

This section contains the economic Key Performance Indicators obtained in the three different case studies. Energy costs, savings, Net Present Value (NPV) and the Internal Rate of Return (IRR) are the indicators calculated and presented as follows.

### 5.5.1 Building level

In this section, building results are showed and assessed individually to understand if the participation in an energy community is beneficial or not and which scenario produces better results in each building typology.

First, annual energy costs and percentage of savings are presented in Table 20 and Table 21. Base case gathers the annual energy cost that each building typology has without self-consumption and SC1, SC2 and SC3 are the different scenarios for self-consumption considered in this work (without EC, in EC, in EC with CBESS).

**Table 20. Annual energy costs per building**

| | | Annual energy costs (€/year) | | | |
|---|---|---|---|---|---|
| **Case study** | **Profile** | **Base case** | **SC1** | **SC2** | **SC3** |
| **CASE A** | SR_46-60 | 387 € | 263 € | 260 € | 141 € |
| | SR_61-70 | 2,218 € | 2,116 € | 2,043 € | 1,776 € |
| | SR_81-90 | 2,340 € | 2,132 € | 2,042 € | 1,743 € |
| **CASE B** | SR_46-60 | 406 € | 276 € | 274 € | 201 € |
| | SR_61-70 | 2,204 € | 2,104 € | 2,030 € | 1,856 € |
| | MR | 4,429 € | 3,431 € | 3,387 € | 2,499 € |
| **CASE C** | SR_46-60 | 439 € | 299 € | 296 € | 210 € |
| | SR_61-70 | 2,408 € | 2,299 € | 1,999 € | 1,835 € |
| | MR | 4,433 € | 3,434 € | 3,200 € | 2,272 € |
| | SCHOOL | 6,324 € | 4,130 € | 3,387 € | 3,069 € |

**Table 21. Annual savings per building**

| | | Annual savings (%) | | |
|---|---|---|---|---|
| **Case study** | **Profile** | **SC1** | **SC2** | **SC3** |
| **CASE A** | SR_46-60 | 32% | 33% | 63% |
| | SR_61-70 | 5% | 8% | 20% |
| | SR_81-90 | 9% | 13% | 26% |
| **CASE B** | SR_46-60 | 32% | 32% | 50% |
| | SR_61-70 | 4% | 8% | 16% |
| | MR | 23% | 24% | 44% |
| **CASE C** | SR_46-60 | 32% | 33% | 52% |
| | SR_61-70 | 4% | 17% | 24% |
| | MR | 23% | 28% | 49% |
| | SCHOOL | 38% | 48% | 53% |

For the residential sector, it is notable the correlation between electricity demand and energy costs, being SR_46-60 the typology with lowest energy costs. Regarding the savings, it is visible how the profiles with less demand (SR_49-60) have higher percentages of savings than the other SR profiles with more demand. School profile is the typology with highest initial savings (38%) as it is the one with highest self-sufficiency due to the coupling between demand and generation.

Concerning IRR and NPV at a building level, Table 22 shows the results obtained in each scenario considered. Regarding scenario 2 and 3, as an approach to estimate the initial investment per building in each case, it has been considered that each building invests according to its PV capacity installed.

It should be noted that, to allow for a broader comprehension of the potential of energy communities deployment beside optimal tecno-economic parameters, PV and battery installation was considered only with energy balance concerns on their sizing. As such, in investments terms, lower KPIs were expected.

**Table 22. IRR and NPV per building**

| | | IRR (%) | | | NPV (€) | | |
|---|---|---|---|---|---|---|---|
| **Case study** | **Profile** | **SC1** | **SC2** | **SC3** | **SC1** | **SC2** | **SC3** |
| **CASE A** | SR_46-60 | 7.2% | 7.3% | -1.4% | 878 € | 937 € | -5,402 € |
| | SR_61-70 | 5.8% | 8.2% | 2.2% | 303 € | 2,303 € | -2,626 € |
| | SR_81-90 | 7.9% | 11.4% | 5.6% | 1,847 € | 2,347 € | 539 € |
| **CASE B** | SR_46-60 | 7.1% | 7.0% | -5.4% | 917 € | 841 € | -8,506 € |
| | SR_61-70 | 5.7% | 8.1% | -1.3% | 286 € | 1,230 € | -5,527 € |
| | MR | 9.5% | 9.9% | 2.5% | 6,270 € | 6,987 € | -8,540 € |
| **CASE C** | SR_46-60 | 7.2% | 7.1% | 0.3% | 973 € | 902 € | -3,320 € |
| | SR_61-70 | 5.7% | 14.0% | 6.6% | 303 € | 4,381 € | 1,348 € |
| | MR | 9.5% | 11.6% | 8.1% | 6,269 € | 9,612 € | 8,111 € |
| | SCHOOL | 7.2% | 8.7% | 0.6% | 12,071 € | 21,091 € | -40,218 € |

Before analysing the results, it is necessary to mention that for the scenarios that consider buildings in an EC (SC2 and SC3), investment costs in each building are defined proportionally to the PV capacity installed. For the first and second scenario, all IRR rates are higher than the discount rate considered (5%), which means viability of the investments. Nevertheless, when comparing with literature review, (Villar, Neves and Silva, 2017; Luthander et al., 2015) the values obtained are low for typical self-consumption investments. This is mainly due to the fact that this work did not consider economic criteria for the sizing of the PV systems, the sizing was assessed by the PV potential on buildings' roofs.

It is important to highlight that, in general, all buildings are benefited when comparing results from SC1 to SC2. When the buildings go from individual self-consumption (SC1) to collective self-consumption (SC2), buildings surpluses are shared, getting better results. Moreover, best results are found in case study C, where the highest increase in IRR and NPV can be found when going from SC1 to SC2. The most benefited building typology in this case is SR_61-70, going from 5.7% to 14% of IRR. These results lead to conclude that collective self-consumption is more attractive as investment than individual self-consumption. Also, better results are found when considering different consumption profiles, as having higher sharing rates.

Regarding the scenario with community battery (SC3), indicators fall down in all typologies and in most cases IRR rates are under the discount rate and NPV are negative, so investments are not considered to be viable and buildings will not be economically benefited in this scenario. The only typology in which IRR maintains above the discount rate is in the MR (8.6%) and slightly in SR_81-90 (5.6%).

### 5.5.2 Energy community level

Regarding the energy community level, this section gathers the economic results obtained in scenarios with collective self-consumption (SC2) and collective self-consumption with CBESS (SC3).

Table 23 and Table 24 present the annual energy costs and savings obtained in the three case studies and considering the different energy community scenarios (without or with CBESS).

**Table 23. Annual energy costs at EC level**

| | **Annual energy costs (€/year)** | | |
|---|---|---|---|
| | **BASE** | **SC2** | **SC3** |
| **Case A** | 31,874 € | 27,414 € | 22,192 € |
| **Case B** | 77,060 € | 60,979 € | 47,489 € |
| **Case C** | 94,345 € | 63,592 € | 50,968 € |

**Table 24. Savings at EC level**

| | **Savings (%)** | |
|---|---|---|
| | **SC2** | **SC3** |
| **Case A** | 14% | 30% |
| **Case B** | 21% | 38% |
| **Case C** | 33% | 46% |

Energy costs increase as the EC demand increases, being case C the one with the highest value. It can be seen how annual costs decrease in all cases when changing from SC2 to SC3. When considering the central battery, imports from the grid drop down, which leads the EC to have higher savings than in the case without the storage system. Case study C is the one with better saving results, 33% and 46%, respectively for scenario 2 and 3. Nevertheless, the case study which benefits more from the CBESS is case B, with an increase of 17 percentual points from SC2 to SC3. As the self-consumption percentage obtained in case study B is 100%, it can be concluded that B is the case study that takes the most advantage of the CBESS.

Table 25 shows the values obtained for the IRR and NPV when considering scenarios in which buildings are considered being part of an energy community, by collective self-consumption (SC2) or collective self-consumption with CBESS (SC3). These values allow to analyse the economic viability of the investments.

**Table 25. IRR and NPV at EC level**

| | **IRR (%)** | | **NPV (€)** | |
|---|---|---|---|---|
| | **SC2** | **SC3** | **SC2** | **SC3** |
| **Case A** | 7.7% | 0.1% | 33,181 € | -128,242 € |
| **Case B** | 9.2% | 1.0% | 107,848 € | -234,757 € |
| **Case C** | 9.7% | 3.3% | 235,986 € | -141,778 € |

When analysing collective self-consumption scenario (SC2), all case studies have IRR values above the discount rate considered (5%) and positive Net Present Values. It is observed an increase of IRR throughout the different case studies. Case study composed only of SR profiles (case A) is the one with the lowest value (8%). Then, when also considering MR profiles (case B), IRR increases until 9.2%. Finally, IRR increases up to 9.7% when the school profile is added to the EC (case C). Therefore, the more different profiles are added to the EC, better are the results.

Regarding SC3, all case studies obtain IRR values below the discount rate and NPV is negative for all cases. These results drop down the viability of the investments due to several reasons. First, neither PV systems nor CBESS are sized following economic criteria. CBESS sizing depends on the daily demand of the EC. Besides, the CBESS is only charged with EC surpluses, the storage system does not get electricity from the grid. Therefore, as seen in figures from section 5.3.2, the level of storage during winter weeks remains in low levels, so there is a lot of available storage capacity during winter that is not being used. This lack of storage usage during the winter is highly impacting in the low economic results in scenario 3. Also, it is important to mention here that at the end of the calculation period of NPV and IRR, the storage system still has 5 years of lifetime. Indicators would improve if the selling of this equipment had been considered.

Moreover, regarding other research works, in (Barbour *et al.*, 2018), IRR falls 4.7 percentual points when adding a community battery to the scenarios considered. When searching on literature, in (Mirzania, Balta-Ozkan and Ford, 2020) it is stated that existing community-owned solar projects in the UK commonly return 4.5% on investment (ECoE, Exeter Energy Community; SELCE).

At this stage, regarding these results it is important to highlight that the financing of energy communities should be supported by public funding programs and policies that help to ensure the viability of these projects. This way, the investment does not depend entirely on the EC participants. In (Mirzania, Balta-Ozkan and Ford, 2020) it is proposed an innovative model of community-owned energy storage and the study suggests UK public institutions to promote and facilitate policy initiatives. They encourage government to help community renewable energy projects that wish to adopt storage technology by offering technical training and promoting partnerships with aggregators and local suppliers.

# CHAPTER 6

## 6 CONCLUSIONS AND FUTURE WORK

The proposed work analyses the performance of buildings in energy communities considering different scenarios by using as input, data from Urban Building Energy Modelling. An urban modelling framework is created and feeds an energy community model, which performance is assessed through main Key Performance Indicators for three different case studies in the neighbourhood of Madre de Deus, Lisbon. Each case study is analysed in three different scenarios: buildings with solar PV production without being part of an EC, being part of an EC or being part of an EC with central storage (CBESS). This section gathers the conclusions reached through the development of this work and states the lines of future work in this area.

First, results at a building level help to analyse the performance and influence for energy communities of different buildings typologies in the scenarios considered. These results prove that the typology most benefited of being part of an EC, in the collective self-consumption scenario, is the single residential house with electric heating, as it is the one with highest increase of self-sufficiency due to the surplus sharing. School buildings reach as well high increase of self-sufficiency by benefiting from the surpluses in residential buildings (especially due to not coincident demand profiles). For the third scenario, when considering the CBESS in the EC, the multi residential typology is the one that most increases the self-sufficiency. Regarding the self-consumption, multi residential buildings are the ones with the best rate, which means that this is the typology that gets benefits more from its own PV generation and has less surpluses, justified in part by their lowest roof area-demand ratio.

Then, through the analysis of the results at an energy community level, scenarios and the different case studies can be compared, achieving the following conclusions. When adding different building typologies, self-sufficiency increases. The highest self-sufficiency value is achieved in case study C. Therefore, these results demonstrate that the diversity of demand profiles is beneficial for the EC, since sharing rates are higher and this increases its self-sufficiency. Besides, when considering the scenario with central storage, self-sufficiency increases 16 percentual points on average for all cases.

Regarding the self-consumption results, it is important to highlight that when having more daylight consumption, surpluses to the grid are lower, achieving better self-consumption ratios. When considering the scenario with the CBESS, case study B achieves 100% of self-consumption, which means that all the PV generation in consumed in the EC. These results lead to think that, as mentioned in the CBESS analysis, what more influences on the final SC value is the relation between daily solar generation and demand curve. As closer are these parameters, more equilibrated will be the charge and discharge of the CBESS and less surpluses will be injected to the grid.

Considering the economical results, it is concluded that collective self-consumption with CBESS (scenario 3) leads to all buildings typologies to reach higher savings when comparing them with the other scenarios. Also, due to the diversity of profiles and its higher self-sufficiency, the case more benefited by savings is the one composed by residential and school buildings (case study C). However, when assessing IRR and NPV, results are not so promising since the PV systems and CBESS were not sized following economic criteria. The building typology with better IRR and NPV is the multi residential, achieving its maximum when the EC includes school buildings (case study C). Scenarios 1 and 2 are considered economically viable, nevertheless, when including the CBESS (scenario 3), the indicators fall. Conclusions drawn from the economic results arise the necessity of support by public institutions and funding programs to enhance the viability of these projects. Moreover, different strategies on the storage performance could be applied to get more profit from it, such as charging from the grid during low energy price periods, such as during the night.

Therefore, through analysing all the results, it is concluded that both environmental and economic benefits are higher when considering energy communities with diverse load profiles (residential and school), as better self-sufficiency results are achieved due to the sharing rates through buildings.

All in all, in this work several advantages for buildings to join energy communities are demonstrated, considering two different configurations: collective-self consumption and collective self-consumption with a central storage system. A reduction on the dependency from the grid is ensured, which gains more relevance in the current energy market context and leads to less economic impact by future variabilities on energy costs. Moreover, it contributes to the achievement of carbon neutral cities through the reduction on GHG emissions. Positive social impact could also be a key benefit, that needs to be mentioned. Community-owned projects could permit low-income and fuel-poor households to benefit from the economic savings given in energy communities. Here is where the relevance of public investment in this sector relies, and which could boost the cities to ensure a social and fair energy transition and move to decentralize the solar deployment.

Finally, this work aims to be an initial effort for developing an energy community dashboard in which the energy community performance for certain building stock selection could be evaluated. As such, it also opens several future work lines which could be explored and are listed below:

- Improve the model by calibrate UBEM with real monitoring data;
- Define more diverse and accurate profiles for UBEM;
- Test different EC PV surplus shares per participant;
- Explore another CBESS performance strategies and optimize the sizing method accordingly.

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# APPENDICES

## Appendix A

This appendix gathers the data flow that City Energy Analyst uses to obtain the main outputs used in this work. Figure 41 shows how building archetypes are defined, Figure 42 shows the data flows used when calculating the demand, Figure 43 illustrate the inputs and outputs for the solar radiation and Figure 44 shows the data flow used when calculating the photovoltaic potential.

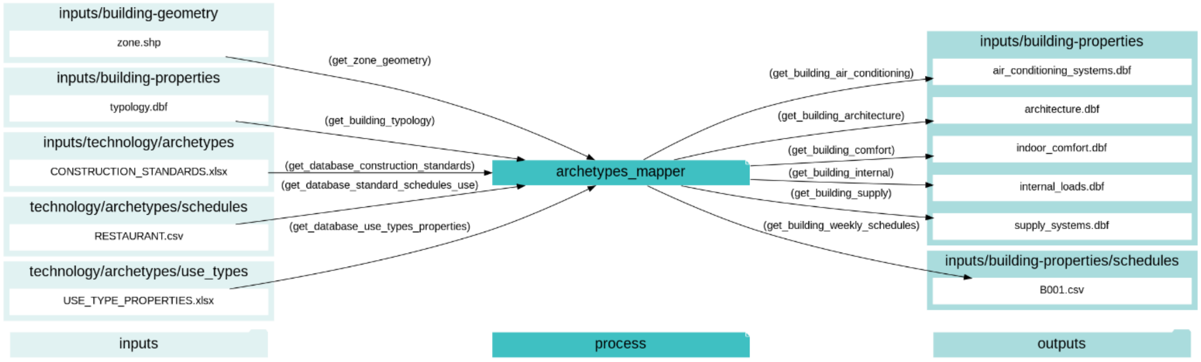

Figure 41. Script data flow for archetypes in CEA (City Energy Analyst)

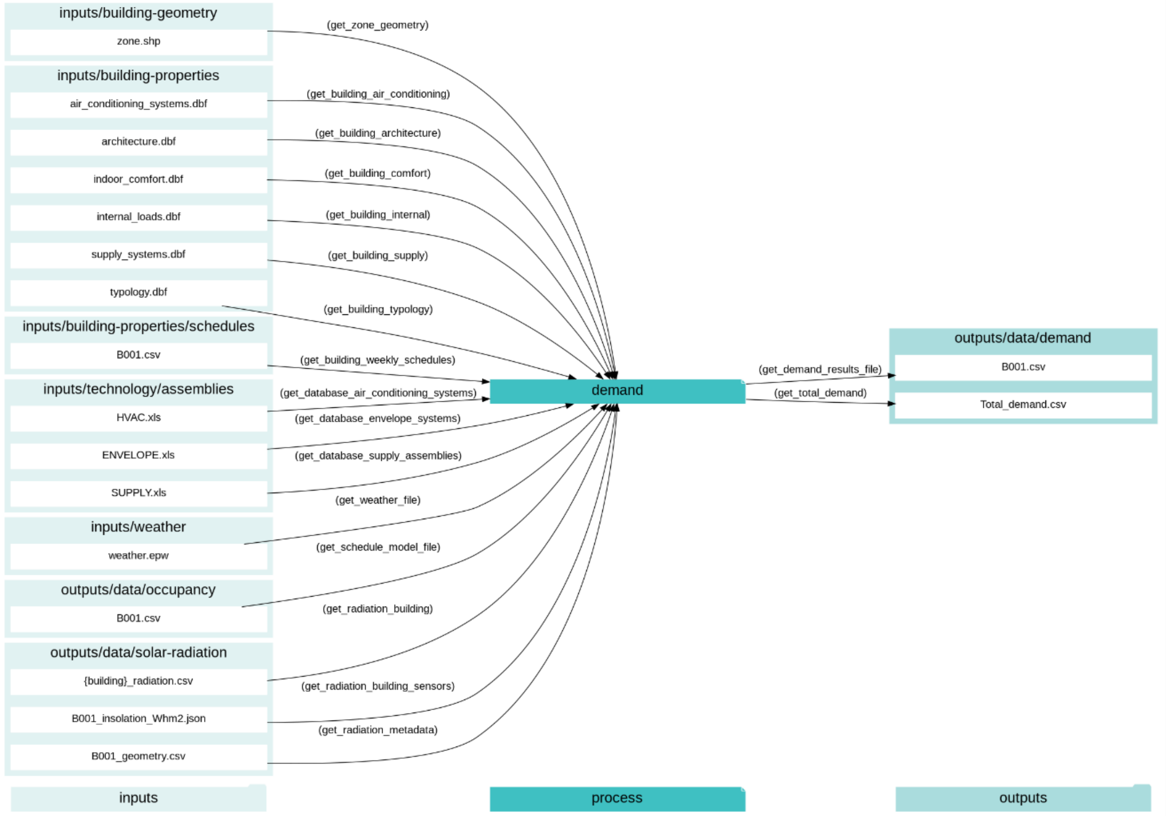

Figure 42. Script data flow for demand in CEA (City Energy Analyst)

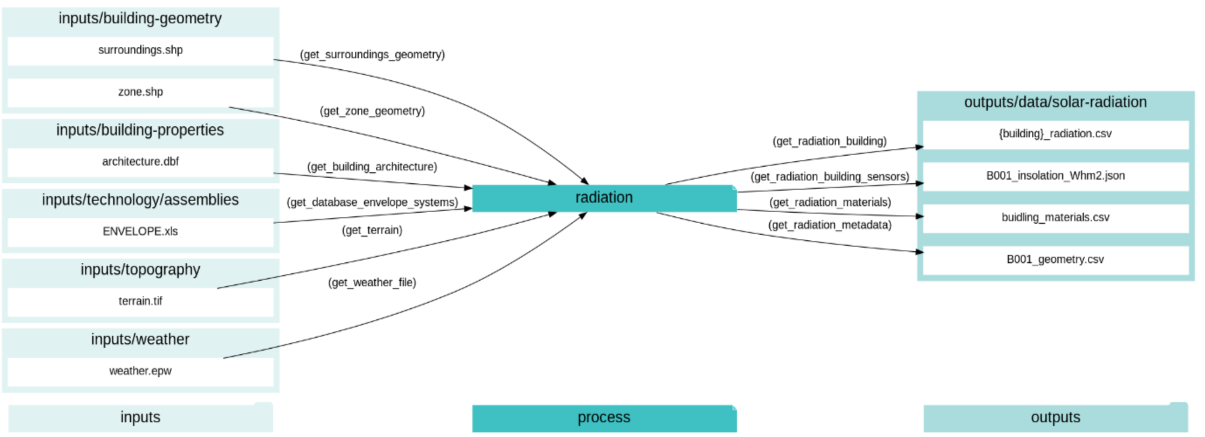

Figure 43. Script data flow for radiation in CEA (City Energy Analyst)

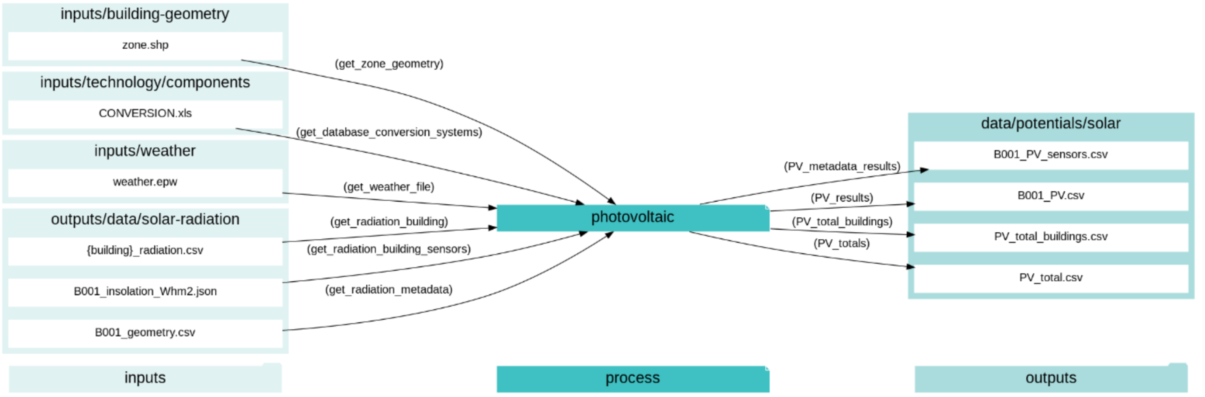

Figure 44. Script data flow for photovoltaic potential in CEA  (City Energy Analyst)

# Appendix B

In the residential sector, the assignment of the buildings with the type of profile is based on statistical data from the specific area where the building is located. Table 26 contains data from the Geographic Information Reference Base (BGRI) regarding the type of families in specific areas of the neighbourhood of Madre de Deus, where the case studies are located. This information is available on the official website of the National Statistics Institute (INE - Censos 2011 Resultados Definitivos).

**Table 26. Distribution of family typologies in each geographic area (INE - Censos 2011)**

| Geographic code | Family with retired | Family with unemployed | Employed family |
|---:|---:|---:|---:|
| 11060701201 | 49% | 12% | 39% |
| 11060701403 | 39% | 9% | 52% |
| 11060701404 | 58% | 8% | 33% |
| 11060701405 | 44% | 11% | 44% |
| 11060701406 | 36% | 7% | 57% |
| 11060701407 | 40% | 7% | 53% |
| 11060701408 | 31% | 17% | 51% |
| 11060701701 | 58% | 8% | 34% |
| 11060701702 | 45% | 5% | 50% |
| 11060701703 | 43% | 6% | 51% |
| 11060701704 | 50% | 0% | 50% |
| 11060701706 | 45% | 10% | 44% |
| 11060702001 | 50% | 13% | 38% |
| 11060702002 | 44% | 6% | 50% |
| 11060702003 | 50% | 0% | 50% |

Table 27 shows the assignment used for single residential buildings. With the number of buildings in each area, percentages from Table 26 are applied to define the number of single residential buildings that will have each profile.

**Table 27. Single residential profiles assigned to each geographic area**

| Geographic code | N buildings/area | N SING_RET | N SING_UNEM | N SING_EMP |
|---:|---:|---:|---:|---:|
| 11060701404 | 40 | 23 | 3 | 14 |
| 11060701405 | 12 | 5 | 1 | 6 |
| 11060701406 | 12 | 4 | 1 | 7 |
| 11060701407 | 18 | 7 | 1 | 10 |
| 11060701408 | 16 | 5 | 3 | 8 |
| 11060701704 | 64 | 32 | 0 | 32 |
| 11060701706 | 50 | 23 | 5 | 22 |
| 11060702001 | 31 | 15 | 4 | 12 |
| 11060702002 | 27 | 12 | 2 | 13 |
| 11060702003 | 23 | 11 | 0 | 12 |

Regarding multi residential buildings, the profile of the whole building is defined with the distribution of family profiles in each area (Table 28).

**Table 28. Multi residential profiles assigned to each geographic area**

| Geographic code | N buildings/area | Family with retired | Family with unemployed | Employed family | Profiles in MR |
|---|---|---|---|---|---|
| 11060701201 | 4 | 49% | 12% | 39% | MULTI_RES_1 |
| 11060701702 | 7 | 45% | 5% | 50% | MULTI_RES_2 |
| 11060701703 | 2 | 43% | 6% | 51% | MULTI_RES_3 |

# Appendix C

This appendix shows the profiles and type of supply assigned to each building in the 3 case studies. Table 29, Table 30 and Table 31 show the definition in each case study.

**Table 29. Buildings profiles and type of supply. Case A**

| BUILDING ID | PROFILE | SUPPLY | | | |
|---|---|---|---|---|---|
| | | APPLIANCES | HOT WATER | HEATING | COOLING |
| B10623 | SING_EMP | ELECTRICITY | NATURAL GAS | NATURAL GAS | ELECTRICITY |
| B10626 | SING_EMP | ELECTRICITY | NATURAL GAS | NATURAL GAS | ELECTRICITY |
| B10630 | SING_EMP | ELECTRICITY | NATURAL GAS | NATURAL GAS | ELECTRICITY |
| B10643 | SING_RET | ELECTRICITY | NATURAL GAS | NATURAL GAS | ELECTRICITY |
| B10666 | SING_EMP | ELECTRICITY | NATURAL GAS | NATURAL GAS | ELECTRICITY |
| B10680 | SING_UNEM | ELECTRICITY | NATURAL GAS | ELECTRICITY | ELECTRICITY |
| B10684 | SING_EMP | ELECTRICITY | NATURAL GAS | ELECTRICITY | ELECTRICITY |
| B10688 | SING_RET | ELECTRICITY | NATURAL GAS | NATURAL GAS | ELECTRICITY |
| B10742 | SING_RET | ELECTRICITY | NATURAL GAS | NATURAL GAS | ELECTRICITY |
| B10753 | SING_RET | ELECTRICITY | NATURAL GAS | NATURAL GAS | ELECTRICITY |
| B10757 | SING_EMP | ELECTRICITY | NATURAL GAS | NATURAL GAS | ELECTRICITY |
| B10776 | SING_EMP | ELECTRICITY | NATURAL GAS | ELECTRICITY | ELECTRICITY |
| B10807 | SING_RET | ELECTRICITY | NATURAL GAS | NATURAL GAS | ELECTRICITY |
| B10812 | SING_RET | ELECTRICITY | NATURAL GAS | NATURAL GAS | ELECTRICITY |
| B10839 | SING_EMP | ELECTRICITY | NATURAL GAS | ELECTRICITY | ELECTRICITY |
| B10849 | SING_RET | ELECTRICITY | NATURAL GAS | ELECTRICITY | ELECTRICITY |
| B10859 | SING_RET | ELECTRICITY | NATURAL GAS | NATURAL GAS | ELECTRICITY |
| B10869 | SING_EMP | ELECTRICITY | NATURAL GAS | ELECTRICITY | ELECTRICITY |
| B10888 | SING_UNEM | ELECTRICITY | NATURAL GAS | NATURAL GAS | ELECTRICITY |
| B10894 | SING_EMP | ELECTRICITY | NATURAL GAS | NATURAL GAS | ELECTRICITY |
| B10898 | SING_EMP | ELECTRICITY | NATURAL GAS | NATURAL GAS | ELECTRICITY |
| B10903 | SING_UNEM | ELECTRICITY | NATURAL GAS | NATURAL GAS | ELECTRICITY |
| B10909 | SING_EMP | ELECTRICITY | NATURAL GAS | NATURAL GAS | ELECTRICITY |
| B10913 | SING_RET | ELECTRICITY | NATURAL GAS | ELECTRICITY | ELECTRICITY |
| B10919 | SING_RET | ELECTRICITY | NATURAL GAS | ELECTRICITY | ELECTRICITY |
| B10925 | SING_RET | ELECTRICITY | NATURAL GAS | ELECTRICITY | ELECTRICITY |
| B10926 | SING_RET | ELECTRICITY | ELECTRICITY | ELECTRICITY | ELECTRICITY |
| B10947 | SING_RET | ELECTRICITY | NATURAL GAS | NATURAL GAS | ELECTRICITY |
| B11056 | SING_EMP | ELECTRICITY | NATURAL GAS | NATURAL GAS | ELECTRICITY |
| B11073 | SING_EMP | ELECTRICITY | NATURAL GAS | NATURAL GAS | ELECTRICITY |

**Table 30. Buildings profiles and type of supply. Case B**

| BUILDING ID | PROFILE | SUPPLY | | | |
|---|---|---|---|---|---|
| | | APPLIANCES | HOT WATER | HEATING | COOLING |
| B10623 | SING_EMP | ELECTRICITY | NATURAL GAS | NATURAL GAS | ELECTRICITY |
| B10645 | SING_RET | ELECTRICITY | NATURAL GAS | NATURAL GAS | ELECTRICITY |
| B10646 | SING_RET | ELECTRICITY | NATURAL GAS | NATURAL GAS | ELECTRICITY |
| B10663 | SING_RET | ELECTRICITY | NATURAL GAS | NATURAL GAS | ELECTRICITY |
| B10666 | SING_EMP | ELECTRICITY | NATURAL GAS | NATURAL GAS | ELECTRICITY |
| B10684 | SING_EMP | ELECTRICITY | NATURAL GAS | ELECTRICITY | ELECTRICITY |
| B10688 | SING_RET | ELECTRICITY | NATURAL GAS | ELECTRICITY | ELECTRICITY |
| B10746 | SING_EMP | ELECTRICITY | NATURAL GAS | NATURAL GAS | ELECTRICITY |
| B10753 | SING_RET | ELECTRICITY | NATURAL GAS | NATURAL GAS | ELECTRICITY |
| B10776 | SING_EMP | ELECTRICITY | NATURAL GAS | NATURAL GAS | ELECTRICITY |
| B10807 | SING_RET | ELECTRICITY | NATURAL GAS | NATURAL GAS | ELECTRICITY |
| B10812 | SING_RET | ELECTRICITY | NATURAL GAS | ELECTRICITY | ELECTRICITY |
| B10839 | SING_EMP | ELECTRICITY | NATURAL GAS | NATURAL GAS | ELECTRICITY |
| B10869 | SING_EMP | ELECTRICITY | NATURAL GAS | NATURAL GAS | ELECTRICITY |
| B10903 | SING_UNEM | ELECTRICITY | NATURAL GAS | ELECTRICITY | ELECTRICITY |
| B11056 | SING_EMP | ELECTRICITY | NATURAL GAS | ELECTRICITY | ELECTRICITY |
| B11073 | SING_EMP | ELECTRICITY | NATURAL GAS | NATURAL GAS | ELECTRICITY |
| B11144 | MULTI_RES_3 | ELECTRICITY | NATURAL GAS | ELECTRICITY | ELECTRICITY |
| B11161 | MULTI_RES_3 | ELECTRICITY | NATURAL GAS | NATURAL GAS | ELECTRICITY |
| B11166 | MULTI_RES_2 | ELECTRICITY | NATURAL GAS | NATURAL GAS | ELECTRICITY |
| B11176 | MULTI_RES_2 | ELECTRICITY | NATURAL GAS | NATURAL GAS | ELECTRICITY |
| B11184 | MULTI_RES_2 | ELECTRICITY | NATURAL GAS | NATURAL GAS | ELECTRICITY |
| B11190 | MULTI_RES_2 | ELECTRICITY | NATURAL GAS | NATURAL GAS | ELECTRICITY |
| B11194 | MULTI_RES_2 | ELECTRICITY | NATURAL GAS | ELECTRICITY | ELECTRICITY |
| B11203 | MULTI_RES_1 | ELECTRICITY | NATURAL GAS | ELECTRICITY | ELECTRICITY |
| B11205 | MULTI_RES_2 | ELECTRICITY | NATURAL GAS | ELECTRICITY | ELECTRICITY |
| B11219 | MULTI_RES_1 | ELECTRICITY | ELECTRICITY | ELECTRICITY | ELECTRICITY |
| B11224 | MULTI_RES_2 | ELECTRICITY | NATURAL GAS | NATURAL GAS | ELECTRICITY |
| B11234 | MULTI_RES_1 | ELECTRICITY | NATURAL GAS | NATURAL GAS | ELECTRICITY |
| B11250 | MULTI_RES_1 | ELECTRICITY | NATURAL GAS | NATURAL GAS | ELECTRICITY |

**Table 31. Buildings profiles and type of supply. Case C.**

| BUILDING ID | PROFILE | SUPPLY | | | |
|---|---|---|---|---|---|
| | | APPLIANCES | HOT WATER | HEATING | COOLING |
| B10623 | SING_EMP | ELECTRICITY | NATURAL GAS | NATURAL GAS | ELECTRICITY |
| B10626 | SING_EMP | ELECTRICITY | NATURAL GAS | NATURAL GAS | ELECTRICITY |
| B10634 | SING_RET | ELECTRICITY | NATURAL GAS | NATURAL GAS | ELECTRICITY |
| B10645 | SING_RET | ELECTRICITY | NATURAL GAS | NATURAL GAS | ELECTRICITY |
| B10646 | SING_RET | ELECTRICITY | NATURAL GAS | NATURAL GAS | ELECTRICITY |
| B10680 | SING_UNEM | ELECTRICITY | NATURAL GAS | ELECTRICITY | ELECTRICITY |
| B10753 | SING_RET | ELECTRICITY | NATURAL GAS | ELECTRICITY | ELECTRICITY |
| B10776 | SING_EMP | ELECTRICITY | NATURAL GAS | NATURAL GAS | ELECTRICITY |
| B10807 | SING_RET | ELECTRICITY | NATURAL GAS | NATURAL GAS | ELECTRICITY |
| B10839 | SING_EMP | ELECTRICITY | NATURAL GAS | NATURAL GAS | ELECTRICITY |
| B10859 | SING_RET | ELECTRICITY | NATURAL GAS | NATURAL GAS | ELECTRICITY |
| B10869 | SING_EMP | ELECTRICITY | NATURAL GAS | ELECTRICITY | ELECTRICITY |
| B10898 | SING_EMP | ELECTRICITY | NATURAL GAS | NATURAL GAS | ELECTRICITY |
| B11036 | SCHOOL | ELECTRICITY | NATURAL GAS | NATURAL GAS | ELECTRICITY |
| B11045 | SCHOOL | ELECTRICITY | NATURAL GAS | ELECTRICITY | ELECTRICITY |
| B11056 | SING_EMP | ELECTRICITY | NATURAL GAS | ELECTRICITY | ELECTRICITY |
| B11073 | SING_EMP | ELECTRICITY | NATURAL GAS | NATURAL GAS | ELECTRICITY |
| B11115 | SCHOOL | ELECTRICITY | NATURAL GAS | ELECTRICITY | ELECTRICITY |
| B11119 | SCHOOL | ELECTRICITY | NATURAL GAS | NATURAL GAS | ELECTRICITY |
| B11144 | MULTI_RES_3 | ELECTRICITY | NATURAL GAS | NATURAL GAS | ELECTRICITY |
| B11148 | SCHOOL | ELECTRICITY | NATURAL GAS | NATURAL GAS | ELECTRICITY |
| B11166 | MULTI_RES_2 | ELECTRICITY | NATURAL GAS | NATURAL GAS | ELECTRICITY |
| B11176 | MULTI_RES_2 | ELECTRICITY | NATURAL GAS | NATURAL GAS | ELECTRICITY |
| B11184 | MULTI_RES_2 | ELECTRICITY | NATURAL GAS | ELECTRICITY | ELECTRICITY |
| B11190 | MULTI_RES_2 | ELECTRICITY | NATURAL GAS | ELECTRICITY | ELECTRICITY |
| B11194 | MULTI_RES_2 | ELECTRICITY | NATURAL GAS | ELECTRICITY | ELECTRICITY |
| B11203 | MULTI_RES_1 | ELECTRICITY | ELECTRICITY | ELECTRICITY | ELECTRICITY |
| B11205 | MULTI_RES_2 | ELECTRICITY | NATURAL GAS | NATURAL GAS | ELECTRICITY |
| B11234 | MULTI_RES_1 | ELECTRICITY | NATURAL GAS | NATURAL GAS | ELECTRICITY |
| B11250 | MULTI_RES_1 | ELECTRICITY | NATURAL GAS | NATURAL GAS | ELECTRICITY |