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Assessment of the potential deployment of energy communities based on GIS approach

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Dedicated to all the members of the Abarde Faria...

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Resumo

À medida que a crescente urbanização do mundo avança, aliada às mudanças climáticas e à degradação ambiental, surge a necessidade de uma mudança de paradigma energético, através da descentralização da produção de fontes renováveis energia. Neste contexto, surge a proposta das Comunidades de Energia (CE), para autoconsumo, usando maioritariamente tecnologia solar fotovoltaica (PV).

Para estudar a possível implementação das referidas comunidades, este estudo visa desenvolver uma ferramenta capaz de, georeferenciadamente, estimar o potencial de produção solar e as necessidades de consumo de energia elétrica, de determinado edifício ou conjunto de edifícios, calculando indicadores de desempenho da CE. A ferramenta foi testada na cidade de Lisboa, para três casos de estudo (quarteirões), com diferentes tipologias de edifícios e orientações solares. Duas abordagens relativas ao potencial de PV a instalar foram testadas, uma primeira onde foi aproveitada toda a área efetiva de telhado disponível, e uma segunda usando apenas área efetiva de telhado suficiente para obter um Net Zero Energy Building.

Os resultados mostraram que a primeira abordagem, onde o excedente de produção elétrica é maior atingindo valores de 90%, depende de um investimento inicial substancial que não é compensado pelos baixos preços a que a mesma é vendido à rede, tornando-a viável apenas em quarteirões com edifícios de baixo rácio de área efetiva vs consumo, e excedentes menores que 70%. A abordagem NZEB quando aplicada reduz os excedentes, onde eles são muito elevados, para valores em torno de 60 % tornando CEs antes impraticáveis em viáveis.

Palavras-chave: Comunidade de Energia, Autoconsumo, Modelação, Net Zero Energy Building

Abstract

As the increased urbanization of the world progresses, allied with climate change and environmental degradation, the need for a paradigm change to decentralized energy systems, with increasing renewable energy supply arises. In this context, Energy Communities (EC) for collective self-consumption, leveraged on solar photovoltaic (PV) energy rise as crucial to meet transition goals.

This study assesses the potential deployment of energy communities, by developing a tool capable of, in a georeferenced way, estimate the solar production potential and the electricity demand needs, of a certain building or set of buildings, calculating key performance indicators to assess EC performance. The tool was tested in the city of Lisbon, for three case studies (city blocks), with different building's typologies and solar orientations. Regarding solar potential, two approaches were taken, a first one where all the available roof effective area was used, and a second one using just enough roof effective area to obtain a Net Zero Energy Building.

The results showcased that the first approach, producing the highest electricity surplus of up to 90%, comes at the expense of a substantial initial investment, which isn't compensated by the low surplus selling prices to the grid. Making this approach economically viable only for city blocks where buildings have smaller roof effective area vs demand ratios and the surplus is smaller than 70% making up for more financially attractive ECs. The NZEB approach when applied reduces the higher surpluses to values of around 60% turning previously impracticable ECs into viable ones.

Keywords: Energy Community, Self-Consumption, Modelling, Net Zero Energy Building

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Chapter 1

Introduction

1.1 Motivation

According to the United Nations, by 2050 68% of the world population will be living in cities. As this urbanization continues, sustainable development is becoming increasingly reliant on successful urban growth management. The rapidly rise of urban populations will cause difficulties in many countries when addressing their needs, including housing, transportation and energy systems [1]. This, allied with climate change and environmental degradation, has led countries to take measures, namely through the Paris Agreement, and in the case of the European Union (EU) to create the European Green Deal, a set of policy initiatives ensuring that in 2050 we will reach carbon emissions neutrality, decoupling economic growth from resource use, and that no one or place is left behind [2]. As part of the Green Deal, a set of intermediate steps towards its' accomplishment have also been released, namely the Fit for 55 package that states the intention of having reduced by at least 55% the greenhouse gas (GHG) emissions by 2030 [3].

For the EU to achieve the defined targets, citizens' participation is of crucial importance, being proposed the organization of citizens in energy communities, as a new business model for the acquisition and deployment of distributed renewable energy production (electricity). They foster a transformation of the energy purchase and sale market of the centralized producer, and retailer-customer relation, along with the expected evolution of renewable technologies such as solar photovoltaic panels, which turn consumers into prosumers. Further, new smart features, as new forms of data storage and exchange, to a decentralized environment in which the individual has the most control over where he buys electricity, who he sells it to, and how much he pays for it, are also emerging [4].

Several studies comparing the current system, which is typically centralized, with a decentralized system using distributed renewable energy sources effectively show that the latter not only provides economic benefits to all parties involved, but also improves transportation and electricity use efficiency, reducing emissions [5]. Two of those studies state that decentralized renewable and non-renewable energy production technologies can achieve reductions in carbon emissions of 65% [6] or 70% [7].

Taking everything into account, it is still unclear which configurations are most beneficial. As a result, being able to model various layouts of energy communities in order to determine which are the most energy and cost efficient based on the types of families and technology involved is of considerable importance.

1.2 Objectives

This Thesis will focus on enabling the assessment of the potential deployment of energy communities, based on GIS available images or software (such as Google Maps or Earth, QGIS, etc), and available open data regarding weather, building characteristics and electricity demand. Thus, the research questions are the following:

- Which rooftop area is optimal for the deployment of ECs? Using the maximum effective area of a rooftop versus using just enough area to make it a Net Zero Energy Building?
- What is the financial impact of different ECs typologies, in different city blocks of Lisbon?

To answer these questions, a MATLAB model was developed to execute the following research goals:

- Determine buildings' roof area, orientation and inclination, and calculate roof incident hourly solar radiation;
- Determine the PV system characteristics to be deployed in each roof, including the hourly electricity production;
- Estimate the number of apartments per building and respective hourly electricity consumption;
- Compute the yearly electricity savings with and without an EC, as well its yearly self-consumption, self-sufficiency and surplus of electricity.
- Report the discounted payback time and internal rate of return for an EC.

1.3 Thesis Outline

This thesis is organized as follows:

- Section 2 presents the literature review on different tools for the analysis of georeferenced images, software to obtain photovoltaic electricity production and on Energy Communities studies;
- Section 3 describes the methodology for the development of the MATLAB tool presented on this work;
- Section 4 showcases the validation of the solar model and the results of EC assessment tool;

- At last in Section 5 the main conclusions of this work are presented as well as its limitations and suggestions for future work.

Chapter 2

Literature Review

The purpose of this chapter is to introduce the essential concepts linked to this dissertation's subject. Firstly, some tools and software to analyze georeferenced images and calculate solar radiation/photovoltaic electricity production are discussed. Then, the context for Energy Communities, their definition and contribution are talked through and lastly two GIS-based energy system models are discussed.

2.1 Tools for the analysis of georeferenced images

In order to accurately identify the physical layers of a georeferenced image, a set of information about the relevant aspects of the surfaces and their surroundings, e.g. a Digital Earth Model (DEM), is necessary. Retrieving this information allow multiple applications such as solar potential calculation, terrain type, etc. Several techniques, such as simple aerial or satellite imaging, Light Detection and Ranging (LiDAR), can be used to collect this type of information [8].

According to the United States Geological Survey, a DEM is a representation of the topographic surface of the Earth's bare ground without trees, buildings, or other surface objects. This type of topographic data is of interest when, e.g there is no need to take into account man made structures. However, when man made infrastructures must be accounted, a digital surface model (DSM) is employed instead. A DSM captures natural and built features on the Earth's surface.This models can be saved in files containing pixels (images) with each pixel having, e.g information on inclination, orientation and/or elevation data [9] [10].

These images can then be processed using a Geographic Information Software in order to create Georeferenced Images. To the United States Geological Survey, *"(...) georeferencing means that the internal coordinate system of a digital map or aerial photo can be related to a ground system of geographic coordinates. A georeferenced digital map or image has been tied to a known Earth coordinate system, so users can determine where every point on the map or aerial photo is located on the Earth's surface.*

The relevant coordinate transforms are typically stored within the image file (...). Georeferencing in the digital file allows basic map analysis to be done, such as pointing and clicking on the map to determine the coordinates of a point, to calculate distances and areas, and to determine other information"[9].

For solar applications, and having the information regarding the relevant features of the surface and their surroundings (DSM), a generic solar radiation model is needed to complete the algorithm [8]. Figure 1 presents the steps and alternatives involved in determining the solar potential of a given location.

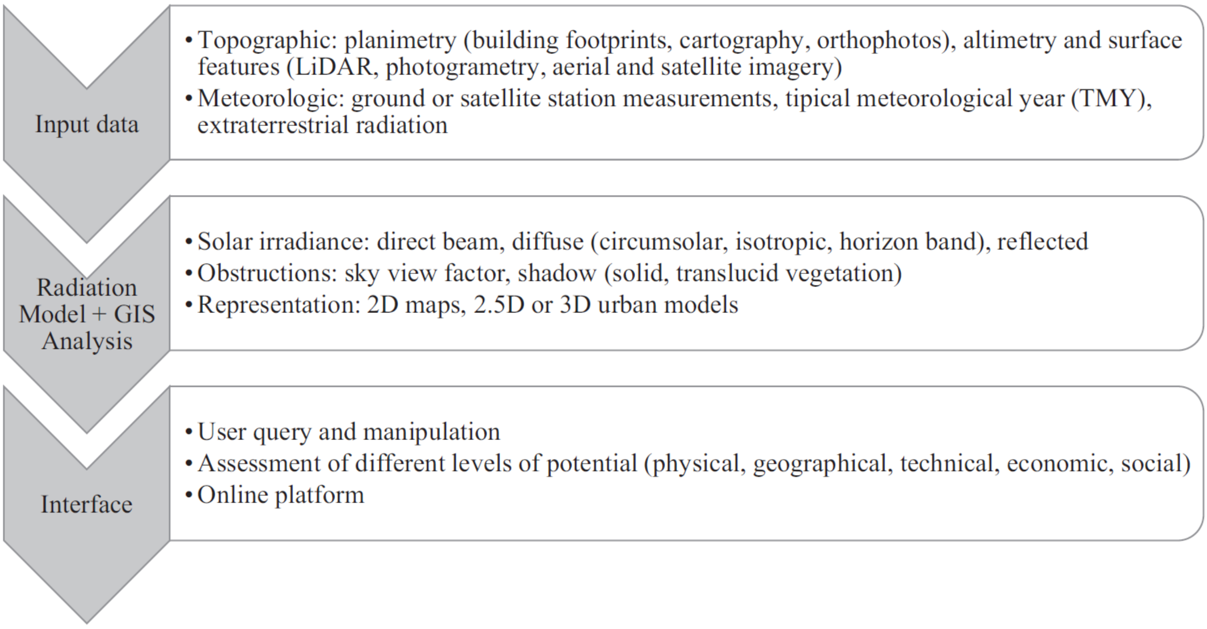

Figure 2.1: Steps and alternatives involved in determining the solar potential of a given place [8].

In the paper titled "Modelling solar potential in the urban environment: State-of-the-art review", Freitas *et al* do a review on several numerical radiation algorithms coupled with GIS tools. Of the several reviewed models, the model developed by Jaroslav Hofierka and Marcel Suri, which is called *r.sun*, was chosen to be analysed in this chapter due to being optimized for European Climate conditions and available for free [8] [11].

2.1.1 r.sun

To describe this model it's necessary to get familiarized with some concepts that will also be used throughout this dissertation such as solar irradiance, the amount of solar power (instantaneous energy) that falls on a unit area on a given time [W/m^2] and solar irradiation, the amount of solar energy falling on a unit area over a specified time interval [Wh/m^2]. Besides these two definitions, radiation can also be separated into three different components: Beam (direct) radiation, is radiation that is selectively attenuated by the atmosphere, is not reflected or scattered, and reaches the surface directly; Diffuse radiation, which is scattered radiation that reaches the earth; and, Reflected radiation, which is the little portion of radiation that is reflected from the ground onto the inclined receiver. Global radiation is made up of these three types of radiation and the r.sun model tries to accurately calculate them [11].

Table 2.1: Inputs and Outputs of r.sun (adapted from [11])

Inputs	• Elevation • Aspect (Panel Azimuth) • Slope (Panel Inclination) • Linke atmospheric turbidity • Ground albedo • Latitude • Clear-sky index for beam component • Clear-sky index for diffuse component • Day number • Solar declination • Local (solar) time • Time step • Sampling distance coefficient for shadowing
Outputs	• Solar incidence angle • Beam irradiance • Diffuse irradiance • Ground reflected irradiance • Duration of the beam irradiation • Beam Irradiation • Diffuse Irradiation • Ground Reflected Irradiation

The r.sun model calculates global radiation from the sum of its beam, diffuse, and reflected components, in clear-sky conditions, not taking into consideration the presence of clouds. To calculate all the different radiation components the model is based on the European Solar Radiation Atlas (ESRA). The model uses several raster inputs and produce raster outputs as well, in Table 2.1 they are listed.

2.2 Photovoltaic Electricity Production Software

2.2.1 PVGIS

PVGIS is a free online solar photovoltaic energy calculator, developed by European Joint Research Center (JCR), for PV systems and solar plants across multiple sites like Europe, Africa, the Mediterranean Basin and South-West Asia. It presents a Google Map application that makes it simple to use. This application evaluates the potential electricity generation of a photovoltaic system, for a defined module tilt and orientation, on a monthly and annual basis, between other features it can optimize the orientation or tilt for a certain geographic location [12].

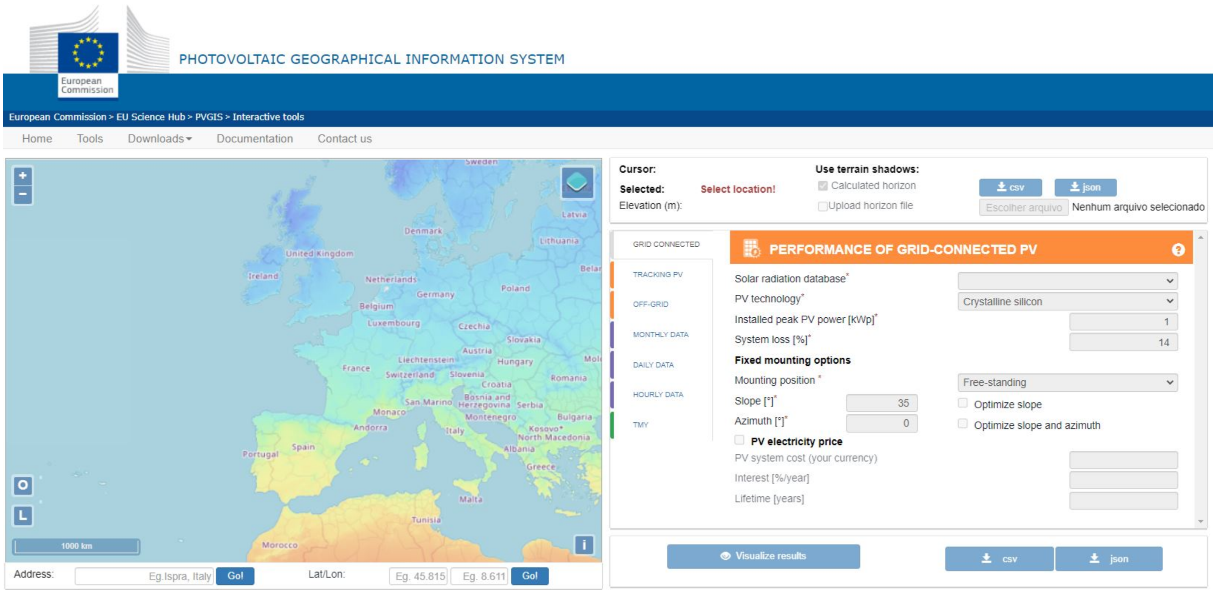

Figure 2.2: PVGIS [13]

2.2.2 PVWatts

PVWatts calculates the solar radiation incident on a PV array using typical meteorological yearly weather data for the desired area. The PV system rating and incident solar radiation are used to determine the energy production for each hour. Users can customize the following system parameters: DC rating, DC to AC derate factor, type of PV array (fixed or tracking), PV array tilt angle, PV array azimuth angle, and local electric pricing [12].

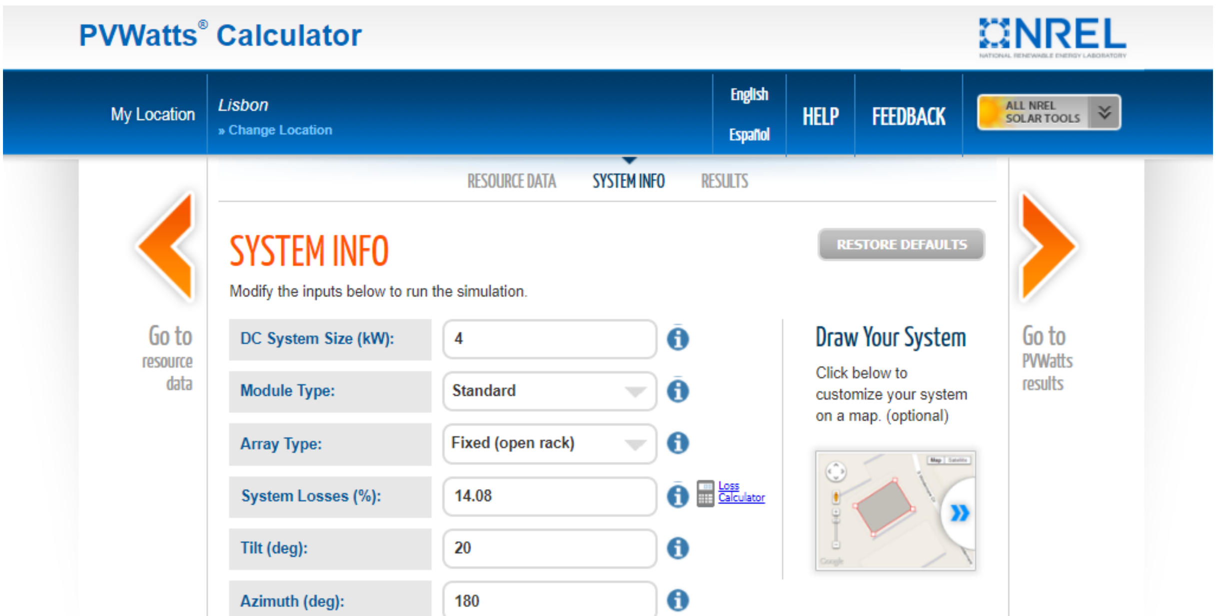

Figure 2.3: PVWatts [14]

PVWatts also offers a tool called *Draw Your System*. The user is directed to Google Maps in a new tab, where they can draw the area of the PV system. The user can either type in the desired capacity or use the drawing feature and select the desired PV efficiency for the calculations. The results show the total for each month, but a file with the hourly or monthly data can also be downloaded [12].

2.3 Distributed Energy Resources

Distributed renewable energy resources refers to the variety of small-scale generation capacity technologies that can be employed to produce electricity near the place of consumption, like solar panels. This paradigm of energy systems, allows the reduction of electricity losses in distribution and transmission lines, and at the same time increase security of supply and uptake of renewable generation. However, it also brings new challenges in the form of grid controlling issues, since the energy supply is no longer coordinated by a central entity. Thus, smart grid managing features have been rising to allow for greater flexibility for grid management, such as demand response (DR), energy storage, time of use tariffs, etc [15]. The DR is the ability to shift electricity demand to match a certain local PV excess, or to respond to real-time electricity prices. This way the consumer can choose when to use certain appliances that might require more or less electricity [15]. Energy Storage is of increasingly interest due to the intermittent nature of renewable electricity production. The ability to store the surplus of electricity during off-peak consumption time and to then inject that stored energy when on peak consumption time is of great value [16].

2.4 Energy communities

As stated on this thesis introduction, for the EU to achieve its defined energy targets for 2050 and also with the Renewable Energy – Recast to 2030 (RED II) raising the target of Renewable Energy Sources consumption by 2030 to 32% , the EU, in 2019, restructured its energy policy framework to aid in transitioning away from fossil fuels and toward greener energy sources. The new directives are now being converted into national laws regarding:

- energy performance in buildings, with specific measures for the building sector to take on issues, updating and altering a number of previously established regulations.
- renewable energy, with the 32% target mentioned above.
- energy efficiency, with the mandate to increase energy efficiency above current levels by at least 32.5% by 2030.
- governance regulation, forcing EU countries to establish integrated 10-year national energy and climate plans for 2021 to 2030.
- electricity market design, build a modern architecture for Europe's electrical system, one that is more flexible, more market-based, and better positioned to incorporate a higher percentage of renewables.

The renewable energy directive also states the inclusion of *new provisions to enable citizens to play an active role in the development of renewables - enabling renewable energy communities and self-consumption of renewable energy* [17][18].

An energy community is, according to Joint Research Centre (the European Commission´s science and knowledge service), *"(...) a wide range of collective energy actions that involve citizen's participation in the energy system (...) and can be understood as a way do "organize" collective energy actions around open, democratic participation and governance and the provision of benefits for the members or the local community".* ECs can be constituted by collectives with varying spatial dimensions (ranging from multi-unit buildings to a neighborhood, municipality, or even entire regions) and can include actors from many sectors (from citizens to local governments or industries). ECs can function with different technologies, such as solar photovoltaic systems, water pumps, wind mills or a biomass power plants, among others. However, given the easy deployment of solar energy on urban environment, namely on building's rooftops, solar PV is the technology more widely used in ECs. In particular, Portugal presents a high suitability of photovoltaic systems, due to the high yearly solar irradiation and therefore electricity production potential in the country (as shown in Figure 2.4) and also the decrease in price and increase in availability of this technology in the last few years [19].

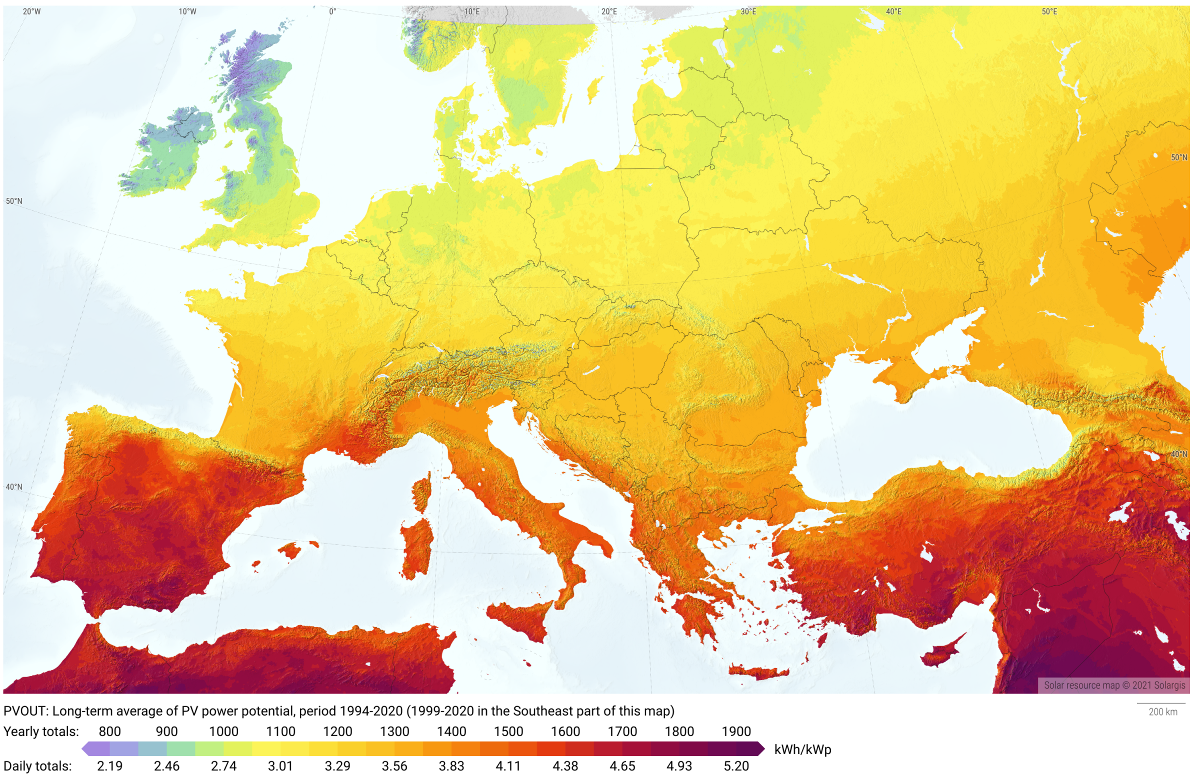

Figure 2.4: Photovoltaic Electricity Potential in Europe [20]

According to [21], recent research has found some evidence of the financial benefits of sharing PV generation among apartment buildings. Large roof areas can provide PV installation economies of scale for apartments, while chances to combine multiple household loads can provide flatter load profiles and encourage self-consumption with projected economic benefits [21]. However, this ratio between available rooftop area versus electricity demand pattern of that same building will determine the viability of the energy community.

2.5 Assessing the contribution of Energy Communities

The evaluation of the impacts associated to the adoption of ECs starts to be addressed in the literature. Ascione et al, addresses the *Optimization of solar energy exploitation for a neighborhood towards nearly zero energy buildings* [22], where an existing neighborhood in the city of Naples (Southern Italy, Mediterranean climate, shoreline) is used as a case study. It is made up of four buildings with gross floor areas ranging between 2082 m^2 to 4082 m^2. To assess the energy modelling and energy retrofit of the neighbourhood, several software are employed into an accurate energy modelling described on Figure 2.5.

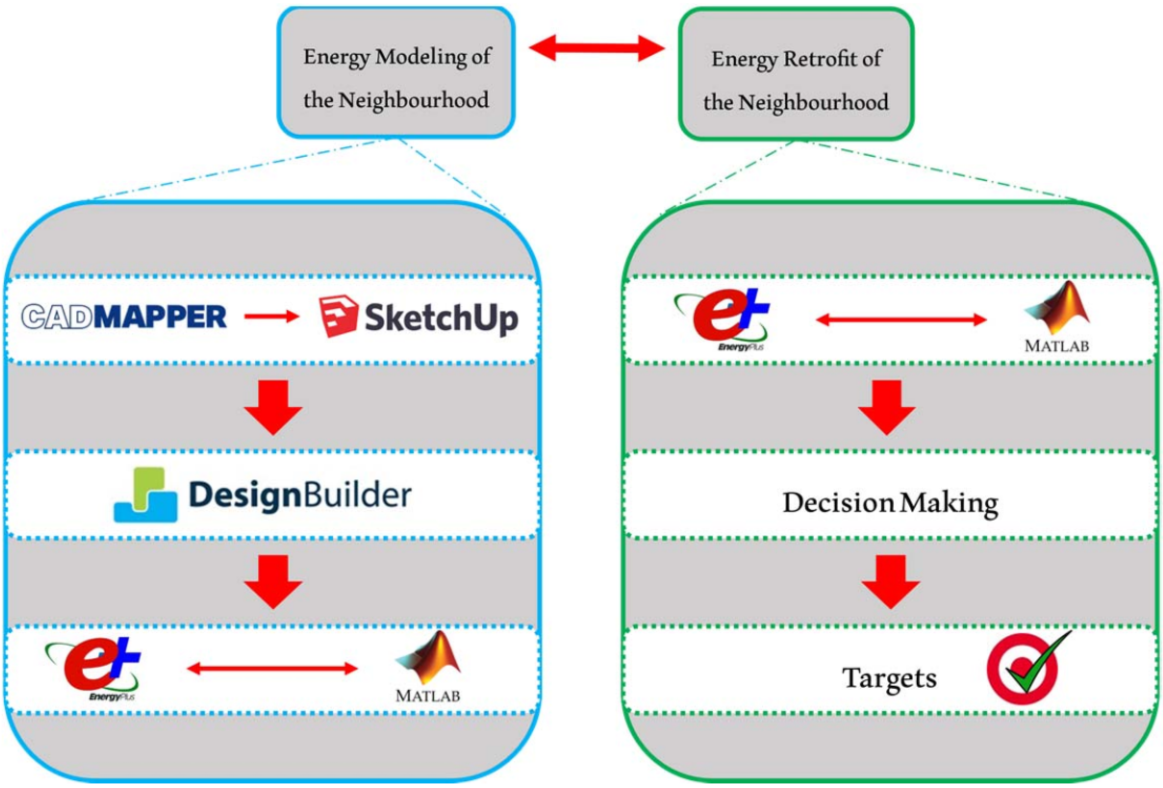

Figure 2.5: Description of the employed energy model [22]

The conjugation of building geometry modelling software and energy ones allows, at the end, to obtain through MATLAB an estimation of the primary energy consumption (electricity) of the four buildings. Also, a retrofit of those energy needs is studied by applying energy efficiency measures to obtain two new different scenarios, a net zero energy one and a cost optimal one for the neighbourhood. Among the retrofitting measures is the installation of PV panels in all the available roof area with share consumption and surplus of electricity sold to the grid. The retrofit measures joined with the PV System show that for the NZEB scenario the CO2 emissions area reduced in 42% and electricity from the grid in 43%, with payback period ranging from 4 to 10 years [22].

Another approach to a self-consumption energy community is done by Luz et al [19]. For a small city in southern Portugal, they simulate three possible energy community's configurations based on collective PV self-consumption. To model the EC that includes city residents and a nearby winery, the Python-based Calliope framework was used. The viability of each design was tested using real electricity consumption data from power transformers and an actual winery, presenting the workflow in Figure 2.6.

One of their scenarios is one of independent self-consumption where the city and the winery do not exchange surplus of electricity and the PV systems are sized considering each of their individual needs. The differences of the Levelized Cost of Energy (LCOE) from the base scenario (no EC) to the Energy Community one can be seen on Figure 2.7.

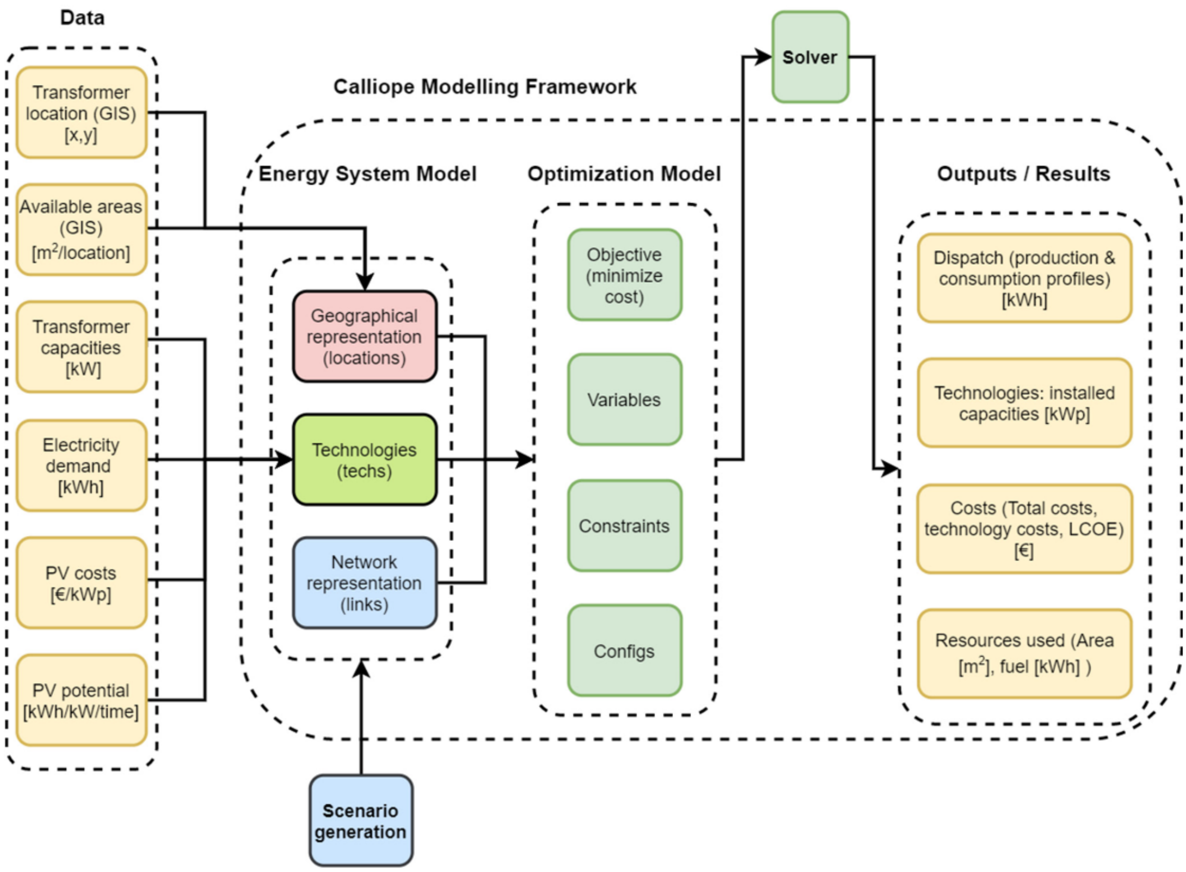

Figure 2.6: Model of the workflow applied in [19]

	City	Winery	Total
PV installed capacity [MW]	3.94	0.70	4.59
Self-sufficiency ratio [%]	31.3	39.5	32.2
Exported electricity [%]	14.4	24.6	15.9
$LCOE_{PV}$ [c€/kWh]	6.58	3.52	6.12
$LCOE_{PV+grid\ costs}$ [c€/kWh]	7.23		6.57
$LCOE_{total}$ [c€/kWh]	16.31	6.78	15.21
Baseline (Scenario 0) $LCOE_{total}$	20	9.8	18.8 (weighted mean)

Figure 2.7: Results for the independent self-consumption scneario [19]

On paper [23], Villar et al, using a techno-economic performance analysis, assesses the suitability and impact of PV systems for self-consumption. Real demand profiles from various sectors as well as simulated solar PV production profiles for various sites, with different panel orientations and tilts, are taken into account. Discounted payback time (DPBT) and interest rate of investment (IRR) are evaluated to determine the optimal prosumer profile. Three different electricity demand profiles (described in Chapter 3.1.4) for residential buildings are considered, and a PV System is associated to each profile with the objective of maximizing the self-consumption. For those three profiles this study finds, self-consumption's ranging from 99% to 93%, DPBTs of 5 to 8 years and IRRs from 8% to 17% [23].

Another different perspective comes from Neves et al, in their paper titled *Peer-to-peer energy trading potential: An assessment for the residential sector under different technology and tariff availabilities*. It's investigated *the potential of P2P energy trading under different available technologies and market paradigms, by analysing the economic benefits for residential consumers and prosumers, given different solar generation contexts and load flexibility levels*, in the Portuguese residential sector [24]. The electricity demand profiles are the ones considered by [23] and described on Chapter 3.1.4. In this study, for each demand load, a PV System is associated creating a prosumer. The PV sizing is a techno-economic sizing considered by Villar et al in [23] plus one 250 Wp PV panel, but also another scenario (high-solar fraction) where the PV size is doubled to encourage the existence of significant PV generation surplus that can be sold on a decentralized market. From the several analyses conducted, one in specific called "Aggregator" can be compared to a self-consumption Energy Community. For this case, in the high-solar fraction scenario, an average of 20% reduction in annual energy costs was observed, as well as 40.6% of electricity surplus and 28% of self-sufficiency [24].

2.6 GIS-based energy system models

On [25] a model for the optimisation of flexibilisation technologies (FlexiGIS) in urban areas is introduced. This model, to be utilized in the city of Oldenburg, is divided into three parts, a first one responsible for the extraction and treatment of buildings data from OSM and using *EnergyMap.info*, a publically accessible data collection website, to obtain the renewable energy sites, type of technology, location and average energy production. A second one, where the temporal dimension is added to the renewable energy sources and electricity consumption open data for different types of buildings is used to model their load profiles. In the last part, the suggested model distributes and minimizes storage capacity at optimal levels of PV self-consumption based on given scenarios and geographical distribution of energy consumption and decentralised storage [25]. An outline of its structure can be seen on Figure 2.8.

This model is still yet under development and the authors leave some of its construction open, such is the case for the calculation of electricity consumption needs for the different buildings, the model also only takes into consideration for its analyses already existing renewable systems through the EnergyMap.info German data source.

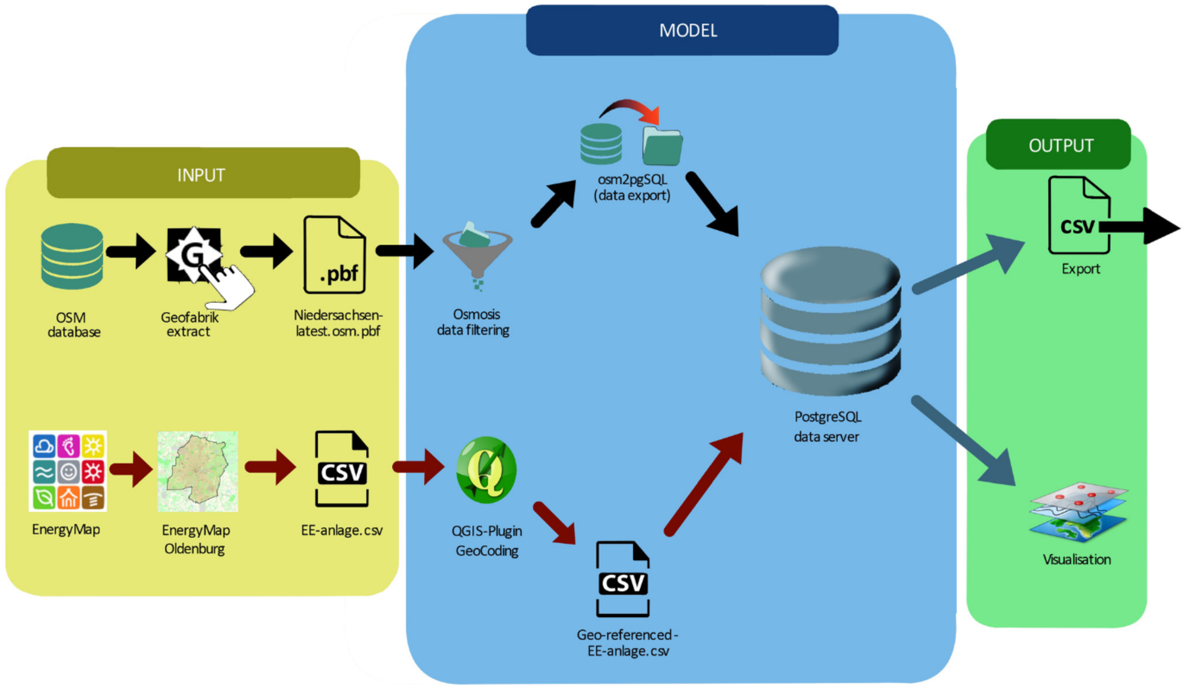

Figure 2.8: Outline of the FlexGis model [25].

Another GIS-based model proposed by Yan-wei Sun et al in [26], which presents a case study for evaluating the potential of solar PV generation at a regional scale using a high resolution grid map of solar radiation and the solar radiation analyst module, ArcGIS 9.3.

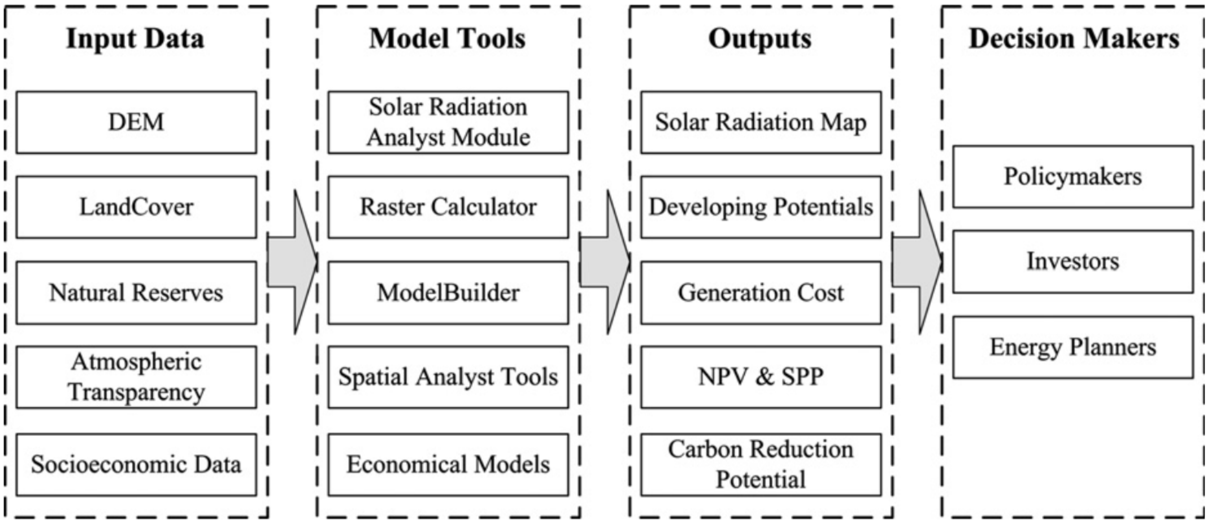

Figure 2.9: Framework of the model proposed by Yan-wei Sun et al [26]

A framework of said model is summarized on Figure 2.9. The model was applied to a Case Study in the Fujian Province, in the southeast coast of China. As can be seen the model calculates a solar radiation map which enables other calculations such as PV electricity production and carbon reduction potential. However, the model does not calculate the consumption electricity needs of each building, just uses a comparison with the total energy consumption in the province [26].

As an example of the outputs of said model, in Figure 2.10 is the annual CO2 reduction potential.

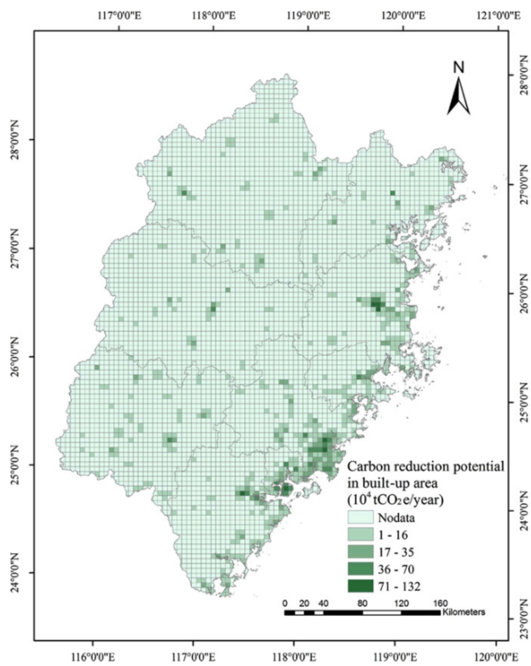

Figure 2.10: CO2 emissions reduction potential [25].

From the analyses done on this chapter, many studies address the topic of Energy Communities potential and the implementation of GIS-models to analyse PV production or create energy models. However there is space for improvement when associating both, that is the challenge addressed on this thesis. To create a tool capable of analysing ECs potential using open-source data for the calculation of individual buildings electricity consumption profile and to cross those profiles with each building PV potential obtained from, also open-source, georeferenced data.

Chapter 3

Methodology

In order to design a model that would allow to perform a preliminary assessment of possible energy community's implementation, the following steps were addressed:

- Select the area for the Energy community implementation;
- Identify building characteristics such as, rooftop orientation, slope, area, number of households per building, etc;
- Estimate the PV electricity production potential for the available rooftop areas, given the solar availability;
- Estimate the buildings' typical electricity consumption profiles, according to families' typologies;
- Calculate key performance indicators of the EC.

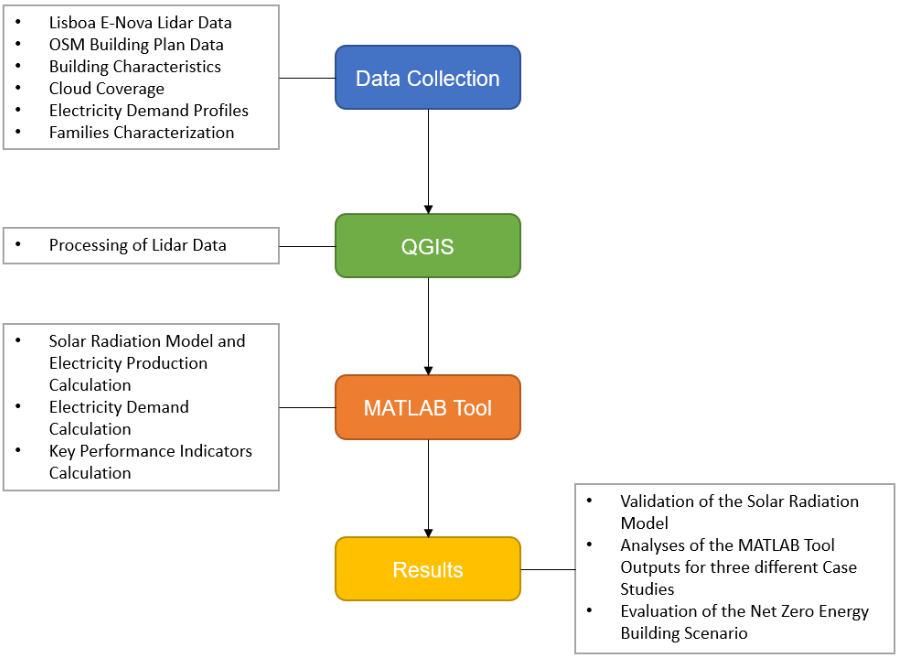

Figure 3.1: Thesis Methodology

3.1 Data Collection

3.1.1 Rooftop orientation and slope

To create a model able to determine the PV electricity production in any desirable location in the city of Lisbon, data regarding roof inclination and orientation for all the buildings was needed. The most viable way to do so was getting Lidar imagery for the entire city. With this need in mind, the Energy and Environment Agency of Lisbon, Lisboa E-Nova [27], who developed the SOLIS Platform, was contacted and they were able to provide three raster files (a matrix of pixels organized in a grid where each pixel contains a value representing information) with pixel wise information regarding all of the city's rooftops' on the following parameters:

- roof inclination;
- roof orientation; and,
- annual incident solar radiation.

In order to analyze the information from the raster files, the images were first processed in QGIS software. Due to the high resolution of the raster files provided by Solis, the data size was too large to be efficiently used in the MATLAB model, so the first step on QGIS was to augment the size of each of pixel from the native $0.16m^2$ to $1m^2$. This allowed for a significant reduction in file size and enabled the manipulation of the files in a way that otherwise would be to computationally intensive and impossible to do on a standard laptop. The next step was to convert the pixels into polygons (raster to vector) converting the Lidar images from a TIF (Tag Image File) into a SHP (shape-file) which is easier to manipulate and visualize on MATLAB. To do so, a function, by the name *raster pixels to polygon*, was used. This function converts a raster layer to a vector layer, by creating polygon features for each individual pixel's extent in the raster layer, employing the QGIS Processing Toolbox, as exemplified in Figure 3.2.

The same procedure was applied to the three files and their information was merged into a single file to reduce data size and for a matter of organization. The two remaining raster files were superimposed on the vector file and from the Processing Toolbox an algorithm called ”Zonal statistics”, that calculates statistics of a raster layer for each feature of an overlapping polygon vector layer was applied, that way saving on each polygon of the vector file all the three desired features: inclination, orientation and incident solar radiation.

Additionally, to the three already discussed features there was also another essential parameter to be determined, known as Bounding Box. This feature is what gives to each polygon its geographic location, it's a set of four numbers, these numbers being geographic coordinates from a certain coordinate reference system (CRS) that limit the edges of each polygon. The data from Lisboa E-Nova used a CRS reference applied only to Portugal, therefore the geographic coordinates were different from the ones used in the World Geodetic System (WGS). As such, a last algorithm from QGIS was employed and the CRS was changed to the WGS making the files ready to be used on MATLAB.

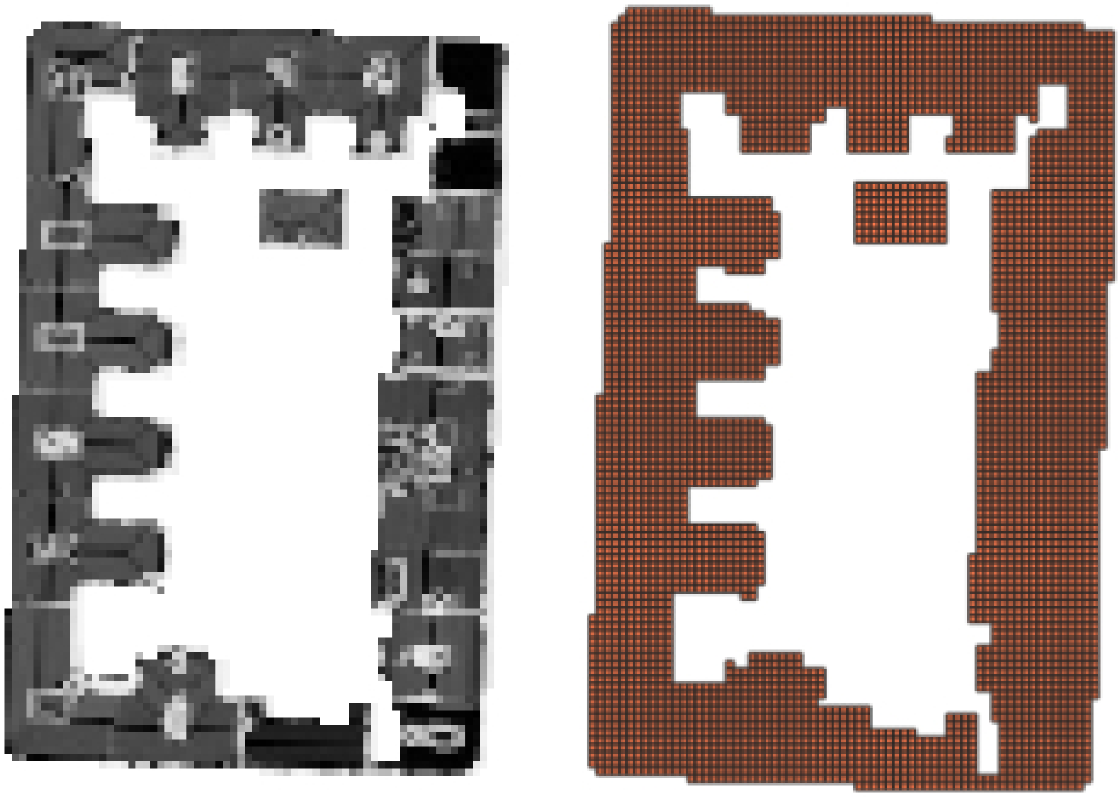

Figure 3.2: On the left a neighbourhood of Lisbon as in the Lisboa E-Nova data (pixels) and on the right after the QGIS algorithm (polygons).

3.1.2 Buildings' area and number of floors

Having all the pixel wise necessary data already in the desired format, the problem that arose was how to associate each polygon to all the different buildings in Lisbon. The way this issue was dealt was by using free available online geographical database from Open Street Map (OSM), where a shape file containing polygons with the outline of every building in the city was retrieved, as seen in Figure 3.3. Other additional features of interest contained in OSM's data were also collected, as the number of floors of each building (not systematically available), and the relative coordinates of the polygons in the selected area, containing the longitude and latitude data for each vertex of the polygon outlining the shape of each building.

For the cases when data regarding number of floors is unavailable, a methodology to consider the average number of floors of that section is used, as described in subsection 3.1.5.

3.1.3 Solar Radiation Model

Having all the data regarding roof inclination and orientation organized and processed, the following step was the calculation of the hourly incident solar radiation in each section of the desired roofs. At this stage an existing Solar Radiation model for MATLAB [28], was adapted. To compute the ground level solar irradiation a variety of parameters needs to be calculated [29] [30], as following detailed.

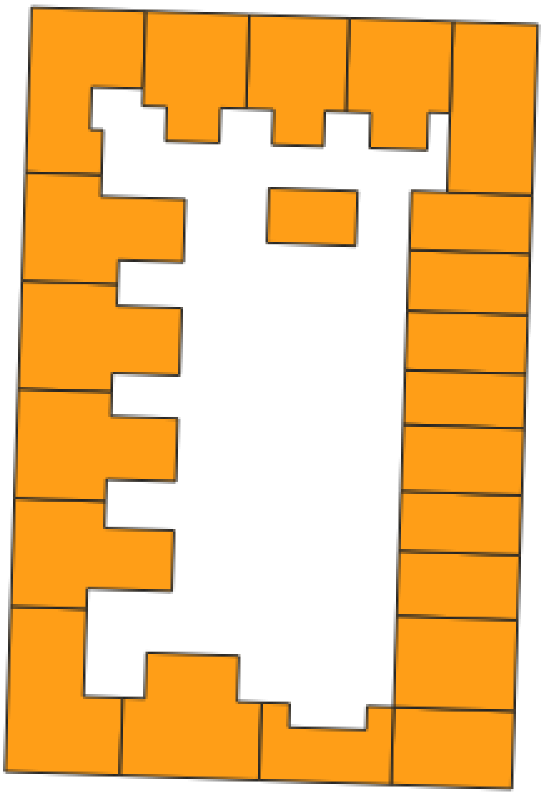

Figure 3.3: The same neighbourhood as in Figure 3.1 this time from OSM's data. (polygons with outline of the buildings)

Azimuth Angle γ

The solar azimuth angle is the angular displacement from the south of the beam radiation projection on the horizontal plane as illustrated on Figure 3.5.

Declination Angle δ

The angular distance between the sun and the earth's equator is measured in degrees of declination. It ranges between 23.45º north and 23.45º south. Seasons are created by the maximum and minimum declination angle values of the earth's orbit, as shown schematically in Figure 3.4.

$$\delta = 23.45 \times sin(360 \times \frac{284 + N}{365}) \tag{3.1}$$

Where N is the day number, from 1 in the first day of January to 365 on the last day of December.

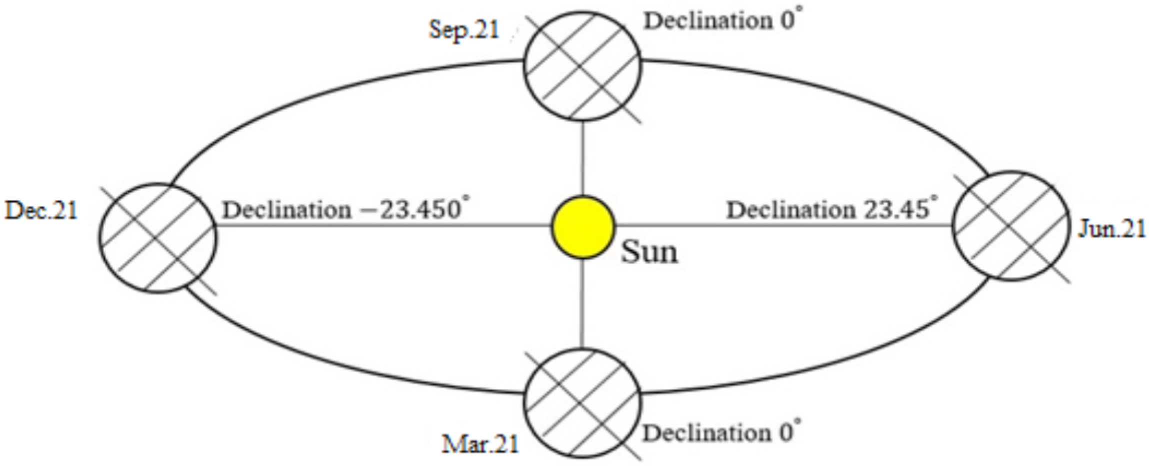

Figure 3.4: Maximum and minimum value of declination angle [29].

Hour Angle, ω

The hour angle is used to describe how the earth rotates around its polar axis, which is comparable to $+15°$ per hour in the morning and -$15°$ per hour in the afternoon.

$$\omega = 15 \times (12 - ST) \tag{3.2}$$

$$ST = LT + \frac{ET}{60} + \frac{4}{60} \times [L_S - L_L] \tag{3.3}$$

$$ET = 9.87 \times sin(2B) - 7.53 \times cos(B) - 1.5 \times cos(B) \tag{3.4}$$

$$B = \frac{360 \times (n - 81)}{365} \tag{3.5}$$

Where LT stands for local standard time, L_S for a local zone's standard meridian, L_L for the study location's longitude in degrees, ET for the equation of time and ST the local solar time. Having defined both hour angle and declination angle, it is also possible to calculate the solar hour at sunrise, h_{sr}.

$$h_{sr} = acos(-tan(L) \times tan(\delta)) \tag{3.6}$$

Solar altitude angle, α

The angular elevation of the Sun above the horizon is the solar altitude angle, α. It is calculated from the local horizontal plane to the sun's center. The angle of the sun's altitude changes on a daily and seasonal basis. Each day, it begins at zero at sunrise, grows as the Sun rises to a maximum at solar noon, and then drops until it reaches zero at dusk.

$$sin(\alpha) = sin(L) \times sin(\delta) + cos(L) \times cos(\delta) \times cos(\omega) \quad (3.7)$$

Where is L is the latitude of the site of study, δ the sun declination angle and ω the hour angle.

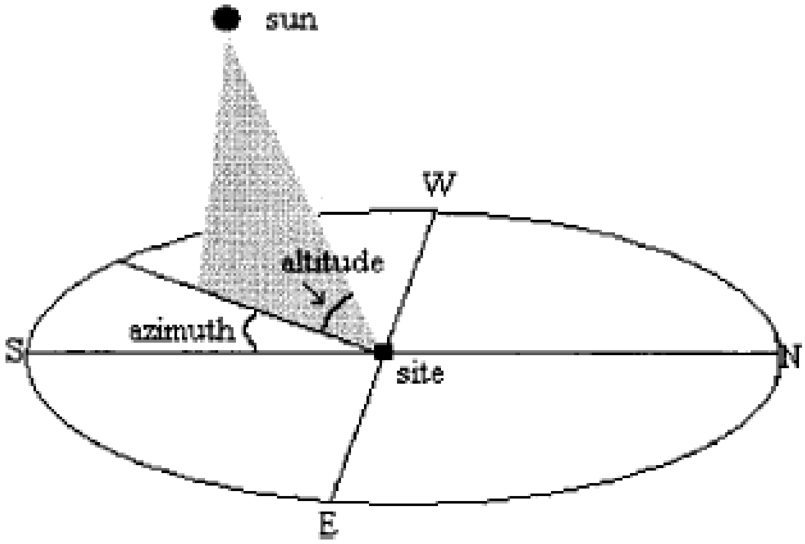

Figure 3.5: Solar altitude and azimuth angle [30].

Extraterrestrial Solar Radiation, I_0

This is defined as the incidence solar radiation outside earth's atmosphere and is calculated as follows:

$$I_0 = S_0 \times (1 + 0.0344 \times cos(\frac{360 \times N}{365}) \qquad (kWh/m^2) \quad (3.8)$$

Where N is the day of the year and S_0 the value of the solar constant which has the value of 1367 W/m^2 according to the World Radiation Centre.

Ground Level Solar Irradiation, I_s

As radiation enters the atmosphere, it is altered by absorption by various gases, molecular scattering by permanent gases, and aerosol scattering due to particles. It is then necessary to have the air mass ratio that is used to calculate the atmospheric transmittance(τ_b) which is in turn used to calculate the solar radiation striking a surface normal do the Sun's radiation(I_s).

$$M = [1229 + (614 \times sin\alpha)^2]^{\frac{1}{2}} - 614 \times sin(\alpha) \quad (3.9)$$

$$\tau_b = 0.56 \times (e^-0.65M + e^-0.95M) \quad (3.10)$$

$$I_s = I_0 \times \tau_b \qquad (kWh/m^2) \tag{3.11}$$

Ground Level Solar Irradiation on a tilted surface, I_p

As the solar panels are to be placed on top of Lisbon roofs, with a certain tilt, solar radiation incident on tilted surfaces must be calculated. The formula that allows that calculation is presented below.

$$I_p = I_p \times cos(i) \qquad (kWh/m^2) \tag{3.12}$$

Where β is the inclination and γ_p the azimuth angle of the tilted surface in study, and cos(i) is equal to:

$$\frac{[sin(\delta)_p \times (sin(L) \times cos(\beta) - cos(L) \times sin(\beta) \times cos(\gamma_p)) + cos(\delta) \times cos(\omega) \times (cos(L) \times cos(\beta) + sin(L) \times sin(\beta) \times cos(\gamma_p)) + cos(\delta) \times sin(\beta) \times sin(\gamma_p) \times sin(\omega))]}{sin(\delta) \times sin(L) + cos(\delta) \times cos(L) \times cos(\omega)}$$

Diffuse and Reflected Solar Irradiation

Lastly, in terms of radiation, one needs to take into account the diffuse irradiation I_d reaching the solar panels. That is, radiation received from the diffusion of a fraction of the global solar radiation on the atmosphere. And also, radiation that is reflected I_r by the earth's surface [31].

$$I_d = \frac{I_0 \times \tau_d \times cos^2(\beta)}{2 \times sin(\alpha)} \qquad (kWh/m^2) \tag{3.13}$$

$$\tau_d = 0.271 - 0.294 \times \tau_b \tag{3.14}$$

$$I_r = \frac{r \times I_0 \times \tau_r \times sin^2(\beta)}{2 \times sin(\alpha)} \qquad (kWh/m^2) \tag{3.15}$$

$$\tau_r = 0.271 + 0.706 \times \tau_b \tag{3.16}$$

Where τ_d is the radiation diffusion coefficient, r is the ground reflectance coefficient and τ_r the reflectance transmissivity.

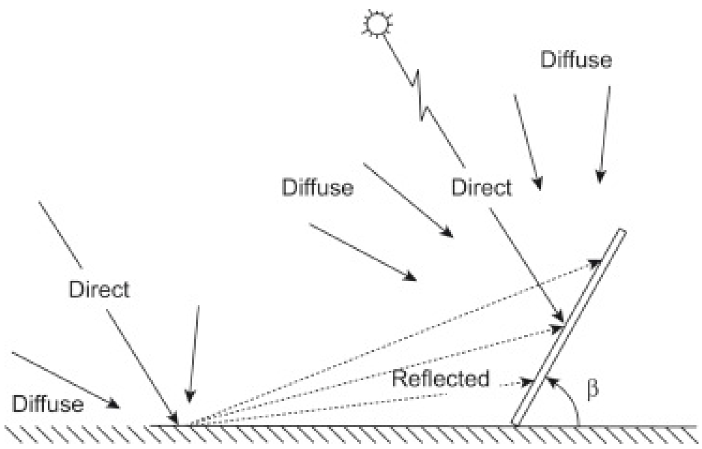

Figure 3.6: Direct, Reflected and Diffuse Irradiation into a tilted surface [31]

Cloud Cover

The formulas presented above for the calculation of solar irradiation at ground level are for clear sky conditions, this means that an adjustment to take into account cloud coverage is needed.

$$I = I_c \times (1 - 0.75 \times n^{3.4}) \qquad (kWh/m^2) \tag{3.17}$$

Where I is the effective solar radiation, I_c the clear sky irradiation and n the cloud cover fraction at the instance of study [32], the weather data regarding cloud coverage is retrieved from *Renewables Ninja* [33] .

3.1.4 Demand data collection

In order to achieve the final goal of assessing Energy Communities outputs, there is the need to know the electricity demand of the households in each building, detailing the hourly load profiles.

Load Profiles

Regarding the load profiles, real data from Project OTGEN was used like in other works such as the one from Vilar et al, defining three consumption profiles [23] [34]:

- C1 - Working Couple, low consumption during the day, with an evening peak, only at home at night
- C2 - Working Couple with two small children, similar to C1, but with peaks during off-peak period, half a day presence at home
- C3 - Working Couple with three teenager children, larger consumer, with high demand during most of the day, a profile that already takes advantage of time-of-use tariffs

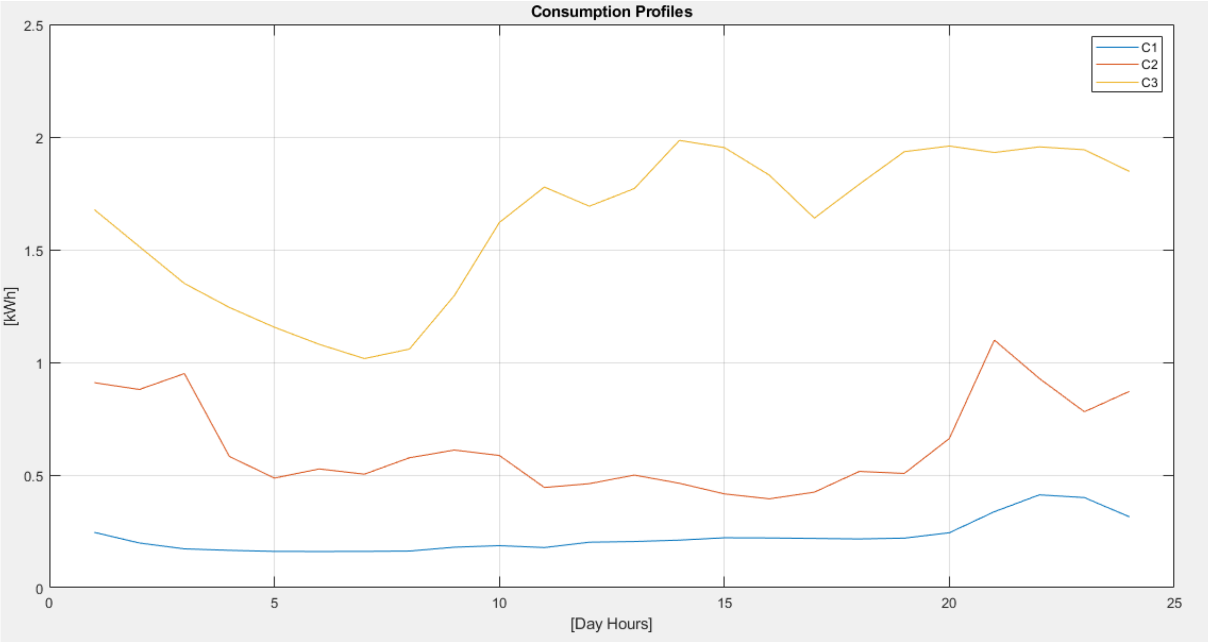

Figure 3.7: Daily Average Consumption Profiles

These three profiles are specific of the residential sector and representative of a database of 68 residential profiles, with a 15-minute temporal resolution, over two years of consumption.

However, to be able to apply these profiles to the households of the selected area, there is the need to determine how many apartments exist on each building and further characterize the families' typologies.

3.1.5 Determination of average building type

As seen before, OSM also provides data regarding number of floors of each building. However, it is not systematically reported for every building. Thus, to calculate the amount of apartments per building, two different approaches were used. When OSM information is available, it is used (equation 3.18), and if not, the average number of floors per building in that BGRI [35] statistical area is used (equation 3.19).

$$N_{D/B} = \frac{N_{D/F}}{N_{F/B}} \tag{3.18}$$

$$N_{D/B} = N_{D/F} \times N_{A_F/B} \tag{3.19}$$

$$N_{D/F} = \frac{A_P}{A_{A/D}} \tag{3.20}$$

Where $N_{D/F}$ is the number of apartments per floor (calculated through Equation 3.20), A_P the projected rooftop area (building plant area), $A_{A/D}$ the average area per apartment, $N_{D/B}$ the number of apartments per building, $N_{F/B}$ the number of floors per building, and $N_{A_F/B}$ the average number of floors per building. The average area per apartment is also retrieved from BGRI [35].

3.1.6 Families Characterization

After knowing the number of apartments per building, there was the need to cross it with the information regarding the types of families on that area. For that, the BGRI [35] data base was once again accessed. As the data available was not quite organized in the three family load profiles, some aggregation assumptions of typologies had to be made, which are further summarized in the following table.

Table 3.1: Families typology used variables from BGRI

BGRI Variable Name:	Description:
n_familias_classicas_1ou2_pess	Families with one or two elements, corresponding to C1 Load Profile
n_familias_classicas_3ou4_pess	Families with three of four elements, corresponding to C2 Load Profile
n_familias_classicas	Total number of families, corresponding to C3 Load Profile

3.2 Tool Development

3.2.1 Buildings' GIS data processing

Firstly, the model takes as an input from the user two pairs off geographic coordinates. These coordinates can be obtained from a GIS software such as Google Earth and should draw a square over the desired location (neighbourhood) to be studied, then it imports to the MATLAB environment the respective data from both shapefiles.

Right after, it removes from the Lisboa E-Nova data all the polygons with an inclination of over 45º that correspond to building edges, skylights or other obstacles that are not part of the actual roof, since in Portugal roofs do not have an inclination of over 45º [36]. The next step was the association of each small $1m^2$ polygon to the respective building which was done using the centroid of the polygons and checking to what building roof they belonged.

3.2.2 Clustering

Due to the nature of the data (Lidar) all the polygons had different values of inclination and orientation even if in the same roof section. Therefore, there was a need to cluster the polygons of the same section. Taking into account that a typical roof does not have more than four different sections/slopes, it was decided to implement a clustering algorithm to divide a roof into four different sections each one with a specific inclination and orientation. Since the orientation data is circular in form (where 0º equals 360º), each polygon had a value of orientation between 0º and 360º (being 0º North and 180º South), thus a circular statistics toolbox for MATLAB was employed. Namely, a function that uses as input the orientation data and the desired amount of clusters, and outputs the data in four groups of polygons with around the same orientation, corresponding to each roof slope. To cluster the inclination data, a

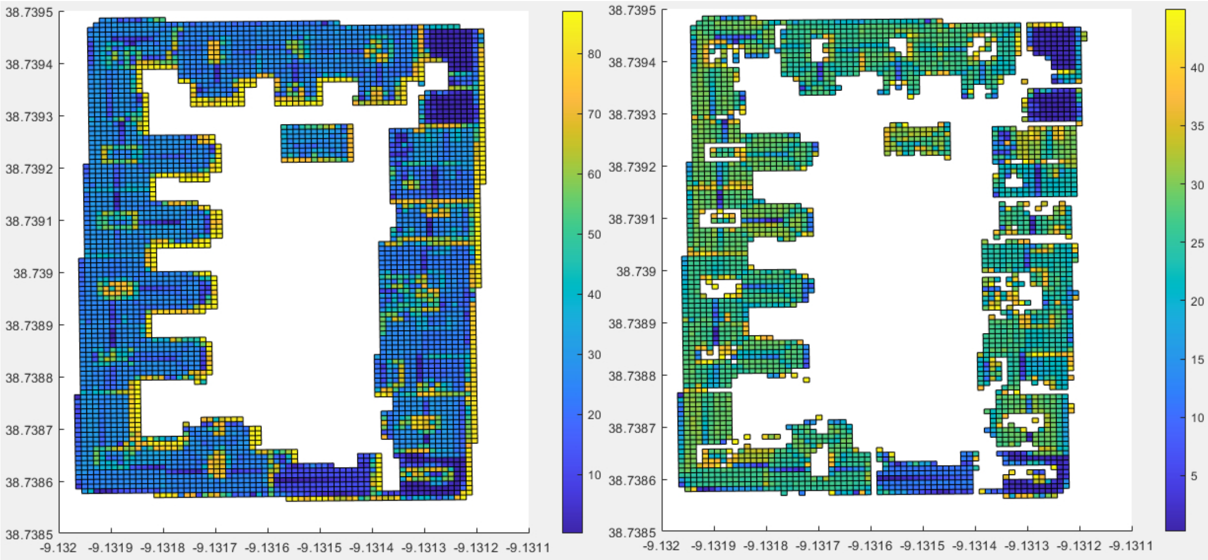

Figure 3.8: On the left the original data and on the right without the polygons with an inclination of over 45º(degrees).

K-means algorithm was applied on top of the orientation circular clustering, outputting for each roof four different sections with the same inclination and orientation [37].

The projected area of each roof is then calculated just by counting the amount of polygons inside each building outline (due to their unitary area), a simple calculation (3.21) is then performed to get the real roof area of each section of each roof, and then the four sections are summed to obtain the real area of the entire roof.

$$A_{roof} = \frac{A_{projected}}{cos(inclination)} \qquad (m^2) \tag{3.21}$$

Where A_{roof} is the real roof area in square meters, $A_{projected}$ the projected area of the roof calculated from Lidar images, and inclination the tilt of the roof.

3.2.3 Solar Potential Algorithm

The solar radiation model algorithm takes as inputs the latitude, inclination and orientation of each roof section, calculating, for every day of the year, the extraterrestrial solar radiation (I_0) and the sun's declination angle (δ), and, four every hour of the day, the hour angle (ω) and the solar altitude angle(α).

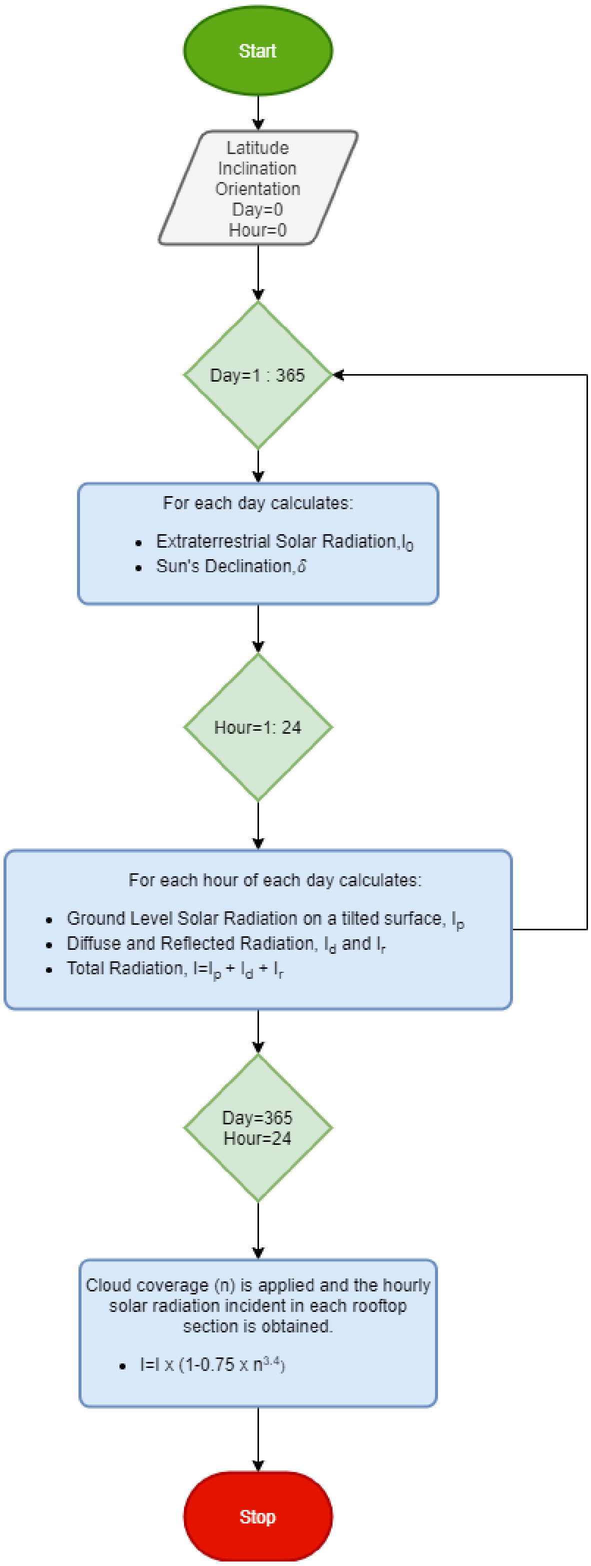

Figure 3.9: Solar Radiation Model Algorithm

As output it calculates the ground level solar irradiation for the inclination and orientation of the roof section(I_p), summing to it the diffuse (I_d) and reflected solar irradiation (I_r). Lastly applying the cloud coverage to obtain for every hour of the year the solar radiation incident on the surface the Earth (I). In Figure 3.9 a flowchart of the algorithm steps is presented.

To validate the created algorithm the values are compared to the ones found on the Photovoltaic Geographical Information System (PVGIS) through the relative error (Eq: 3.22):

$$RE(\%) = |\frac{I_{PVGIS} - I_{Algorithm}}{I_{PVGIS}}| \times 100 \tag{3.22}$$

Were RE is the relative error, I_{PVGIS} the yearly solar radiation in kWh/m^2/year found on PVGIS and $I_{Algorithm}$ the yearly solar radiation in kWh/m^2/year calculated by the developed model.

3.2.4 Effective Roof Area and PV System Implementation

Having calculated the hourly solar radiation incident at the rooftop level, it is possible to estimate the PV production potential. However, we need to make assumptions about the PV systems' characteristics. Firstly, using the approach of Google Project Sunroof [38], only rooftop sections with at least 75% of the maximum annual solar radiation for the city of Lisbon, which is 1994 kWh/m^2 for a surface facing south with an optimum tilt angle of 33º, according to PVGIS[13], are considered eligible to install solar panels.

The solar photovoltaic module used, as well as the inverters and installation cost, was retrieved from the Portuguese company Macolis [39], and is further detailed in the following table.

Table 3.2: Solar PV Module Characteristics

	Solar PV Module
Name	MEPV 120HALF-CUT
Power	340 W
Dimensions	1684 x 1002 x 35 mm
Area	1.68 m2
Efficiency	20.23%
Cost	189.10 €

The number of solar panels to deploy in each rooftop was calculated through equation 3.23, while equation 3.24 is the one used to calculate the amount of electricity produced hourly for each roof section. To estimate the total cost of implementation of the PV system equation 3.25 was used.

$$N_p = \frac{A_r}{A_p} \tag{3.23}$$

Where N_P is the total amount of solar panels to place in each rooftop, A_r the rooftop area of the eligible sections and A_P the area of a solar PV module.

$$E_{rs}(h) = I_{rs}(h) \times A_{rs} \times \eta \times P_R \qquad (kWh) \tag{3.24}$$

E_{rs} is the electricity produced hourly by each roof section, η the solar panel efficiency, I_{rs} the hourly incident solar radiation, A_{rs} the eligible roof section area and P_R the performance ratio of a rooftop PV which according to [40] is of 0.7341. To calculate the electricity produced by each rooftop the production for each section is simply added.

$$C_r = N_p \times C_P + C_I + C_L \tag{3.25}$$

For the cost of implementation, C_r is total cost, in euros, for each rooftop,N_P the number of installed solar panels, C_P the cost of a solar panel, C_I the cost of an inverter (2400€ per inverter needed) and C_L the cost of labor/installation (a function of the amount of solar panels installed).

3.2.5 Families Characterization Algorithm

The MATLAB algorithm starts by evaluating the percentage of each type of family in the desired statistical area. Then it calculates the total amount of apartments and average area per apartment per building (Eq: 3.18, 3.19).

Associating the BGRI data with the available consumption profiles a compromise is defined by associating the ”C1” consumption profile with ”Families with one or two elements”, ”C2” with ”Families with three of four elements” and ”C3” with the remaining which are families with five or more elements. Knowing the percentage of representation of each type of family, it is applied to the amount of apartments in each building, being the final consumption profile of each building for every hour of the year calculated through equation (3.26).

$$Consumption_{P/B} = (F_{1,2} \times C1 + F_{3,4} \times C2 + F_{5,+} \times C3) \times N_{D/B} \qquad (kWh) \tag{3.26}$$

Where $Consumption_{PB}$ is the hourly electricity consumption per building, $F_{1,2}$ the percentage of families with one or two elements in that statistical area,$F_{3,4}$ the percentage of families with three or four elements and $F_{5,+}$ the percentage of families with five or more elements.

3.3 Key Performance Indicators

In order to evaluate the overall performance of an Energy Community some key performance indicator were chosen:

3.3.1 Economic KPIs

- Yearly electricity cost for each building without an EC:

$$E_{Cost} = \sum_{t=1}^{8760} E(t)_{consumption} \times Price(t)_{EDP} \qquad (euros) \tag{3.27}$$

Where $Price_{EDP}$ is the hourly retail tariff in €/kWh and $E_{consumption}$ is the hourly kWh consumed by a building without taking part on an EC.

- Yearly revenue for each building from selling surplus electricity to the grid is:

$$E_{Revenue} = \sum_{t=1}^{8760} E(t)_{surplus} \times Price(t)_{OMIE} \qquad (euros) \tag{3.28}$$

Where $E_{surplus}$ is the hourly surplus of energy produced throughout the year in a building with an EC and $Price_{OMIE}$ 90% the yearly average , of the price defined by the OMIE organization for which electricity can be sold to the main grid, with a minimum value of 0.039€/kWh, a maximum of 0.063€/kWh and an average value of 0.05€/kWh .

- Yearly savings in electricity due to the EC for each building:

$$E_{Savings} = E_{NotConsumed} \times Price_{EDP} + E_{Revenue} \qquad (euros) \tag{3.29}$$

Where $E_{NotConsumed}$ is the electricity a building avoids buying to the main grid due to the collective self consumption from PV systems.

- Internal rate of return for the investment on the EC:

$$IRR : \sum_{t=0}^{N} \frac{E_{Savings}}{(1+IRR)^t} - EC_{Cost} = 0 \tag{3.30}$$

Where N it's the amount of years for which the IRR is being evaluated and EC_{Cost} is the initial investment on the implementation of the EC.

- Discounted payback time for the investment on PV systems on an EC:

$$DPBT : \sum_{t=0}^{N} \frac{E_{Savings}}{(1+d)^t} - EC_{Cost} = 0 \qquad (years) \tag{3.31}$$

Where d is the discount rate and has a value of 6.5%.

3.3.2 Environmental KPI

- Yearly CO_2 emissions for each building:

$$CO2_{Emissions} = E_{Grid} \times (CO2_{Generated}/kWhp) \qquad (tons) \tag{3.32}$$

Where $CO2_{Generated}/kWhp$ is the average kilograms of CO_2 emitted by the consumption of electricity from the grid and E_{Grid} is the the electricity consumed from the grid.

3.3.3 Energy KPIs

- Percentage of self-sufficiency (SS) for each building:

$$SS(\%Totalconsumption) = 1 - \frac{\sum_{t=1}^{8760}(E_{Consumption} - E_{Production}) > 0}{E_{consumption}} \quad (3.33)$$

Where $E_{Consumption}$ is the amount of electricity consumed hourly and $E_{Production}$ the amount of electricity produced hourly in a building.

- Percentage of self-consumption (SC) of electricity for each building:

$$SC(\%Totalproduction) = 1 - \frac{\sum_{t=1}^{8760}(E_{Production} - E_{Consumption}) > 0}{E_{production}} \quad (3.34)$$

- Percentage of surplus for each building:

$$S(\%Totalproduction) = \frac{\sum_{t=1}^{8760}(E_{Production} - E_{Consumption}) > 0}{E_{production}} \quad (3.35)$$

3.4 Net Zero Energy Building

A NZEB, as the name indicates is a special case when the electricity consumed by a building throughout a year its equal to its PV system production.

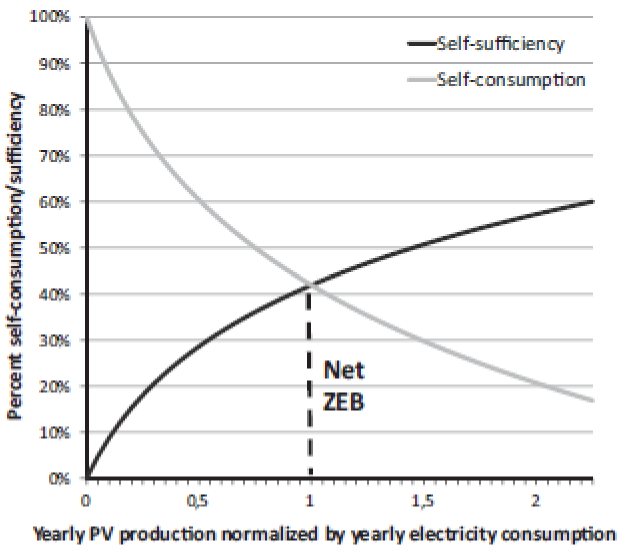

Figure 3.10: Net Zero Energy Building Point [41]

This point is also the point where the building's SC its equal to its SS. This point is found for the cases where the iterative decrease in the PV system size from the maximum effective rooftop area results on an equality of these two values.

3.5 Scenario Design and Comparison

To analyse the results produced by the developed model, three different locations in Lisbon were chosen and in the following section those three case study's are described. In this section, the methodology involved in the analyses of the results produced for those case studies are described.

Firstly, for each case study two types of Energy Community are considered: 1) Each building of the selected zone is an EC by itself, where the participants are only the families living in the apartments of that building, and 2) the entire selected zone is an EC and the participants are all the families living in the apartments of the selected zone.

For the first case, three buildings are selected, and for the other cases only one is selected to do an extended overview. All the roof sections values for orientation, inclination and incident yearly solar radiation are displayed and compared. After this the average building and the total EC are introduced and total values for incident radiation, available roof area, electricity production and consumption are shown. Secondly the KPIs are also displayed and commented for the buildings chosen in Chapter 3.6. For the economic ones, when regarding electricity consumption, two retail tariffs are considered: a simple flat tariff where the price of electricity is always the same at 0.1445 €/kWh, and a dual tariff where electricity from 23pm to 8am is cheaper at 0.0924 €/kWh, and during the rest of the day is 0.1836 €/kWh based on the prices offered by EDP, a Portuguese electric utility company [42].

Lastly, the effective area for the PV System installation is reduced in order to obtain the NZEB, and the economic KPI's are reviewed and discussed for this case.

For the following two case studies the results are displayed in the same way and a comparison is made with the results of the previous case studies.

3.6 Case Study Definition

3.6.1 Case Study 1

From a city block in the parish of Areeiro, 22 buildings were selected to study the results of a conceptual EC. Two different analyses were made, the first is considering each building as an EC community by itself, the participants being the families living in each building. The other one was considering the 22 buildings as a large EC called Total EC (TEC). Figure 3.11 is an aerial image from Google Earth showcasing the city block at study. It is important to point out that from the BGRI data this neighbourhood has relatively small buildings, with an average of three floors and three apartments (families) per building,

Due to the large amount of data generated for the twenty two buildings, only three were selected to do an extensive overview. One building having the major sections of the roof facing North and South (Building 1), another with its roof sections facing East and West (Building 2) and lastly one building with a flat roof (Building 3) . In Figure 3.11 the three selected buildings can be seen. After that, the results for an EC composed of all the 22 buildings and an average building were also analyzed.

Figure 3.11: City Block in Areeiro

3.6.2 Case Study 2

Figure 3.12: City Block in Areeiro with higher buildings

For the second case study in this work, it was decided to choose city-block of Lisbon where the selected buildings are higher and therefore have more apartments than the ones on Case Study 1, to infer how it influences the results. A total of 5 buildings were selected, also in the parish of Areeiro, which can be seen on Figure 3.12.

Like in Case Study 1 it was decided to consider both scenarios, one where each individual building is an EC and another where all the buildings together compose an EC. To analyze the results given by the model it was decided to, in this case, select only a building to do an extensive overview (Building 1 in Figure 3.12) as well as the average building and the Total EC.

3.6.3 Case 3 Study

The third and final case study in this project is a city-block made up of eight buildings in Parque das Nações. The reason for this selection is the age of the structures, notably the fact that this city block is relatively new when compared to the previous two. The EC situations are the same as in the previous cases, and, as in Case Study 2, only one building (Building 1 in Figure 3.13) is chosen to provide a comprehensive perspective alongside the average building and the whole EC.

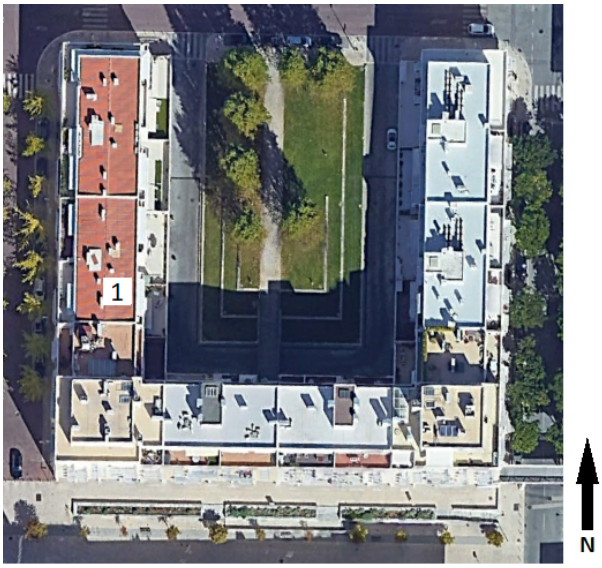

Figure 3.13: City block in Parque das Nações

Chapter 4

Results

This section starts with the validation of the developed solar radiation model and then it proceeds into the analysis of the data outputted by the MATLAB tool for the three selected Case Studies in the city of Lisbon.

4.1 Solar Radiation Model Validation

First, the solar radiation model was validated in order to have accurate values to feed in the EC assessment model.

The following table summarizes the comparison between the yearly radiation values, for the specified roof inclination and orientation of three random building roofs from the first Case Study city block, given by the developed model and the values found on the European's Commission Photovoltaic Geographical Information System (PVGIS) [13]. The data is organized by the orientation of the roofs, North encompassing orientations from 314º to 45º, East is 46º to 135º, South is 136º to 225º and West is 226º to 315º.

Table 4.1: Orientation and Inclination of different roof sections in the three selected buildings

Building:	**Roof Section Orientation (°):**				**Roof Section Inclination (°):**			
	North	**East**	**South**	**West**	**North**	**East**	**South**	**West**
A		88.4	213.6/137.2	279.6		24.8	32.5/28.6	26.6
B	3.7	109.2	178.2	242.2	23.6	5,8	14.6	7.9
C		89.5/89.5	219.1	271.7		21.7/32.7	36.6	25.5

Table 4.2: Yearly Solar Radiation values error between the developed model and the data from PVGIS

Building:	**Relative Error (%):**				**Average Error (%):**	**Error Standard Deviation (%):**
	North	**East**	**South**	**West**		
A		1.24	1.76/0.19	5.03	2.71	2.33
B	8.35	2.79	1.94	3.45		
C		1.6/0.15	1.63	4.46		

Inspecting Figure 4.1, Table 4.1 and Table 4.2, the radiation calculated by the developed model is very

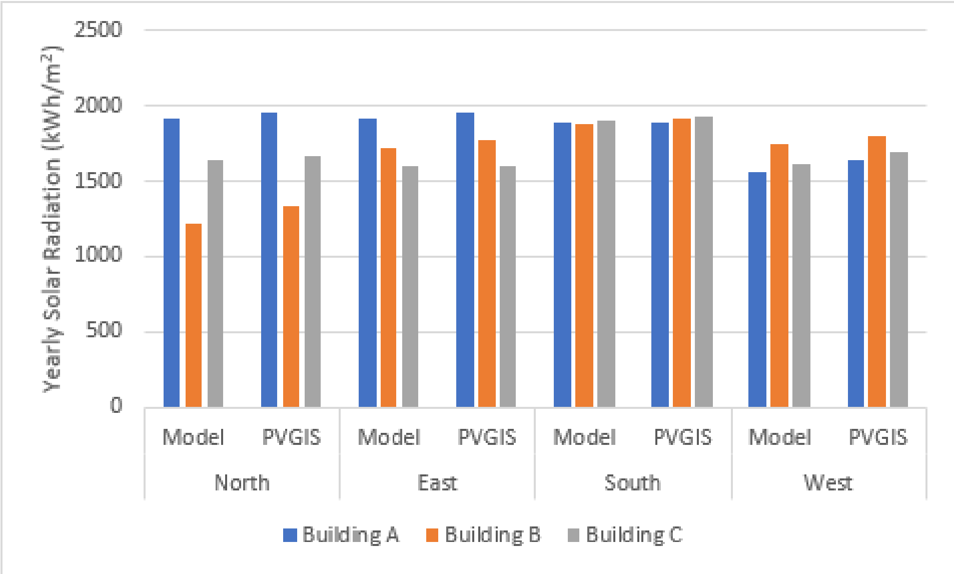

Figure 4.1: Yearly Incident Solar Radiation on each roof section

close to the values found on the European Commission's data base (around 2.7%). Taking into account the relative errors found for solar radiation models in *Review and statistical analysis of different global solar radiation sunshine models* [43], one can determine that the results from the developed model are accurate enough to be trusted and produce faultless values that can be used on the rest of this work.

4.2 Roof Sections Orientation, Inclination and Yearly Solar Radiation for Case Study 1

Tables 4.3 and 4.4 show the first results outputted by the model, the orientation and inclination data organized in four different sections (clusters) per rooftop and the yearly incident radiation on each section.

One preliminary observation can be made regarding the pronounced differences in radiation values for the different orientations. When the roof orientation is North, or closer to it, the radiation values are smaller, so much so that they are below the 1495$kWh/m^2/year$ threshold, and are removed from consideration, as seen on Tables 4.5 and 4.6. When they are facing South, the maximum values of radiation are observed. For East or West, the values are in-between the ones observed for South and North facing rooftop sections.

Case Studies 2 and 3 present a similar behaviour and the tables with their data can be consulted on Appendix A.

Table 4.3: Orientation and Inclination of the different roof sections in the three selected buildings

Building:	**Roof Section Orientation (°):**				**Roof Section Inclination (°):**			
	North	**East**	**South**	**West**	**North**	**East**	**South**	**West**
1	358.7	102.3	184	264.4	24.5	25.6	23.7	24.5
2		56.5/92.6		272.6/309.1		26.2/27.2		23.5/29.7
3	358.8	106.7	201.9	273.9	11.5	13.9	6.8	11.0

Table 4.4: Yearly Incident Solar Radiation on the different sections of the three roofs

Building:	Roof Section Yearly Incident Solar Radiation (kWh/m2/year):			
	North	East	South	West
1	1200.7	1709.2	1943.4	1656.0
2		1390.7/1642.7		1619.6/1304.3
3	1483.7	1729.8	1781.7	1661.7

Table 4.5: Orientation and Inclination of different roof sections in the four buildings after the threshold for minimum accepted yearly incident radiation

Building:	Roof Section Orientation (°):				Roof Section Inclination (°):			
	North	East	South	West	North	East	South	West
1		102.3	184	264.4		25.6	23.7	24.5
2		92.6		272.6		26.2/27.2		23.5
3		106.7	201.9	273.9		13.9	6.8	11.0

Table 4.6: Yearly Incident Solar Radiation on the different roof sections in the four buildings after a threshold for minimum accepted yearly incident radiation

Building:	Roof Section Yearly Incident Solar Radiation (kWh/m2/year):			
	North	East	South	West
1		1709.2	1943.4	1656.0
2		1642.7		1619.6
3		1729.8	1781.7	1661.7

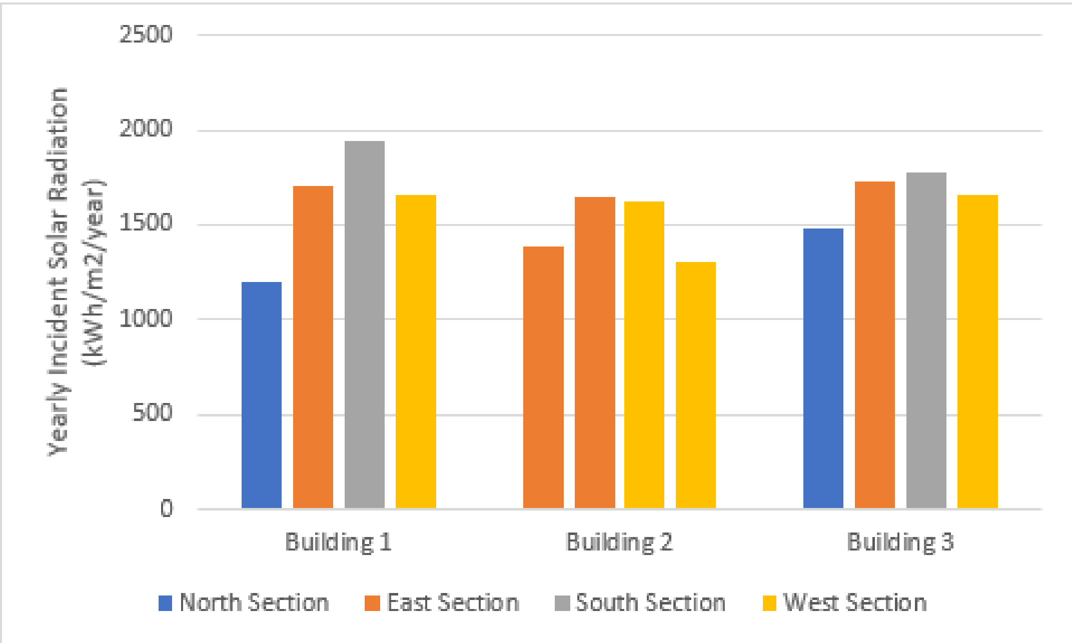

Figure 4.2: Yearly Incident Solar Radiation on the different roof sections of the four buildings

Figure 4.2 showcases how the orientation and inclination of the roof section take a part on the amount of incident yearly solar radiation. Building 1 has a roof section facing North and the radiation value is significantly lower when compared to the other ones. In the case of Building 3 the inclination data for the rooftop polygons doesn't reflect a totally flat roof, due to the small inclination values of its roof sections the orientation is a factor to take into account and the values of radiation for the different roof sections are very similar but not identical. Despite the fact that none of the sections in Building 2 face north, two of them are close enough to have an annual incidence radiation below the stated threshold, while the other two, which face West and East with a 180-degree difference, having similar values.

4.3 Roof Area and Radiation, Case Study 1

Inspecting Figure 4.3 one can see how the effective roof area (area where the yearly incident radiation is above the threshold) is significantly smaller when compared to the total area for Building 1, this happens because Building 1 has a large roof section facing North with a low yearly incident radiation that is discarded.

On the other hand, almost all roof area for Buildings 2 and 3 is effective. In the case of Building 2, its larger sections are facing East and West having a good amount of yearly solar radiation, only the other two sections with a relatively small area are eliminated. Building 3 has a section directly facing North (358.83º) and, because this section is not exactly flat (11.4º of inclination), the amount of yearly solar radiation is also below the defined threshold and was removed from consideration. As expected, the Average Building (AVB) is similar to the other buildings and the Total EC (TEC) also follows the same relation as the average building, being the sum of all rooftops into a larger one.

In Figure 4.4 the total yearly incident radiation is compared to the effective one and, even though incident radiation depends on many factors, it is easy to see that proportionally the difference is fairly similar to the area difference.

The results for this section regarding the other two Case Studies can be consulted on Appendix B enabling a similar analysis.

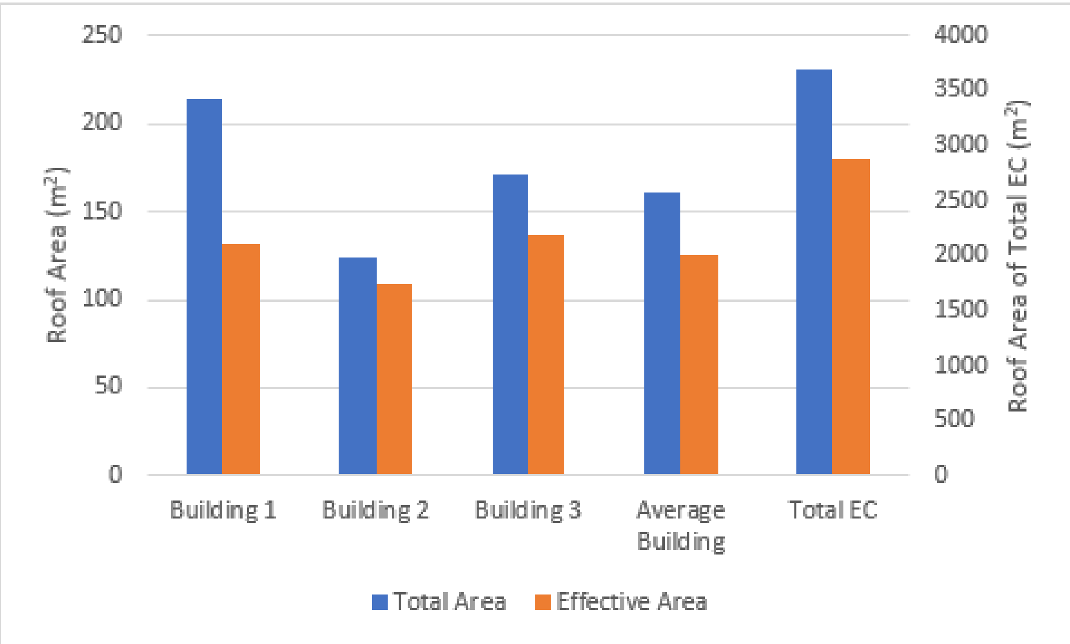

Figure 4.3: Total Area vs Effective Area for the installation of a PV system

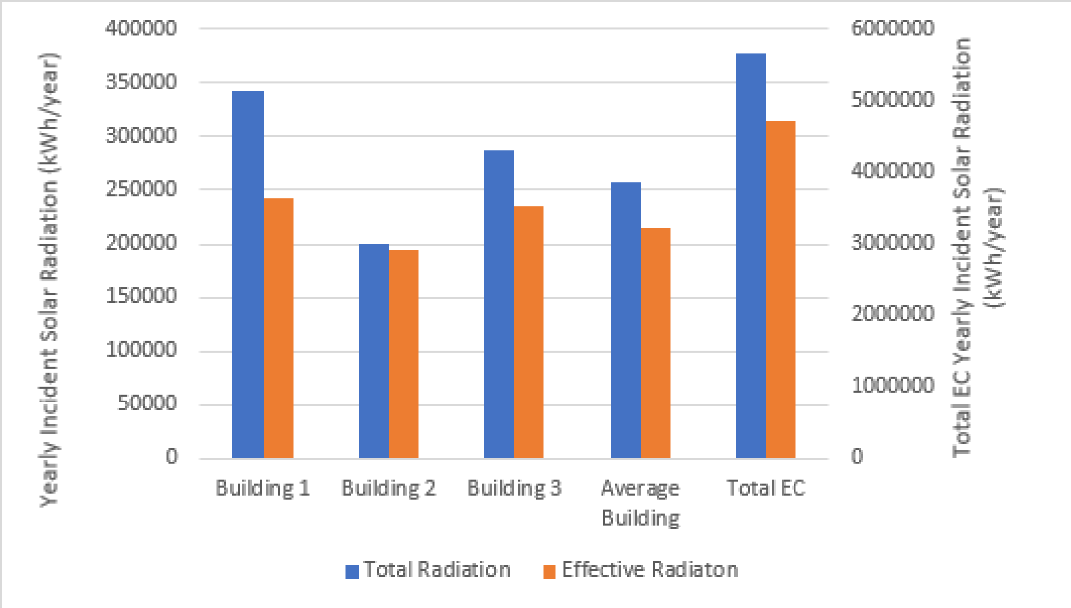

Figure 4.4: Total Radiation vs Useful Radiation for the installation of a PV system

4.4 PV System

It was decided to utilize all the roof effective area to install solar panels, taking into account the characteristics of each panel already mentioned in the Methodology. The number of installed solar panels per roof and yearly electricity production can be seen on Table 4.7. It is interesting to notice how in Case Study 1, even though Building 3 is the one with the higher amount of solar panels, it is not the one with the highest electricity production. Building 1 with a roof section directly facing South provides better solar exposition throughout the year, meaning a higher electricity production in a smaller area.

Table 4.7: PV Systems Characteristics and Outputs from the MATLAB tool

Building:	Number of Solar Panels:	Investment Cost (€):	Yearly Electricity Production (kWh):
		Case Study 1	
1	78	24449	36003
2	64	21802	26354
3	81	25017	35053
AVB	74	23693	31841
TEC	1702	521254	700523
		Case Study 2	
1	160	39956	74505
AVB	168	41594	72995
TEC	1012	249569	437973
		Case Study 3	
1	153	71374	64415
AVB	134	63508	57436
TEC	1079	508065	459489

For the second and third case studies, the costs of investment are higher due to the larger effective area, which means more solar panels but also more electricity production, more than double compared to the Average Building of Case Study 1.

4.5 Families Typology and Electricity Consumption

4.5.1 Typology of the families in the city block under study

Figure 4.5 shows the percentage of each of the three considered families for the three case studies, retrieved from the BGRI data. For Case Study 1, working couples are clearly the majority of the families, which will mean the greatest influence when it comes to electricity consumption, as shown on Figure 4.6.

The family's typology on the second Case Study is slightly different from the previous one, where the percentage of working couples is smaller, and there are more couples with two young children changing a bit the consumption profiles of the families living here.

The type of families living in the zone of Lisbon selected for Case Study 3 have quite of a significant change when compared to the previous selected ones, the percentage of working couples (53%) is significantly smaller as well as the couples with three children that represents only 1%, meaning an increase in couples with two young children for almost 50%, which produces a fairly different consumption curve (Figure 4.10).

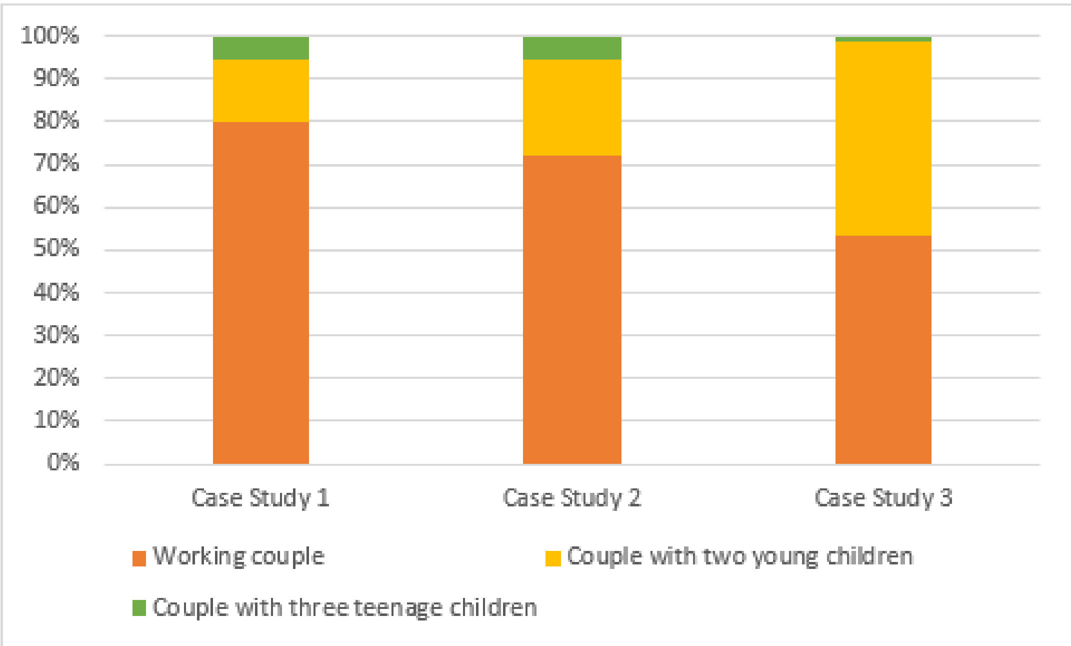

Figure 4.5: Typology of the families in the city block under study.

4.5.2 Electricity Consumption

Each hourly loads (C1, C2, C3) are associated with each type of family (as denoted previously), thus the buildings' hourly load profiles will be different according to the percentage of types of families and number of apartments per building, as so the yearly electricity demand, as observed in Table 4.8.

For Case Study 1 and 2, from Figure 4.6 and 4.8, it is possible to observe how a large percentage of working couples influences the neighbourhood daily consumption profile, since when compared to Figure 3.7 the consumption's profiles are mostly close to the "C1" profile. For Case Study 3 in Figure 4.10 the consumption profiles are mix of the "C1" and "C2"

Table 4.8: Electricity Consumption

Building:	**Number of Apartments:**	**Yearly Electricity Consumption (kWh):**
Case Study 1		
1	6	18914
2	2	6304
3	4	12609
AVB	3.6	11320
TEC	83	249041
Case Study 2		
1	32	109961
AVB	32	109961
TEC	192	659769
Case Study 3		
1	15	56029
AVB	15	56029
TEC	120	448233

4.6 Daily average electricity demand vs Solar production

4.6.1 Case Study 1

In Figure 4.6 the daily average electricity demand and supply for each building is shown. As expected, the production of electricity starts only at 6 o'clock which is the earliest sunrise hour for Lisbon, and it stops at 21 o'clock which is around the latest sunset.

Going through Figure 4.6, it is easily noticeable how the PV electricity production vastly surpasses the consumption needs during the sun-shining hours of the day. The effective area used is far greater than the necessary to just satisfy the self-consumption needs of each building, this happens due to the high effective roof area per apartment, that translates into higher PV power installed and electricity production, as can be seen on Figure 4.12.

Taking a closer look into Figure 4.7, one immediately notices how the self-sufficiency is nearly the same for all the cases. Even though they all have different amounts of installed PV power and consumption profiles, due to a far greater electricity production than consumption needs during the day, the SS tends to be around 42% as can be seen on Figure 4.6, from around 8 am to 7 pm the consumption needs for all cases are satisfied by production, only a small discrepancy happens during the early and late sunshine hours hence the nearly identical SS.

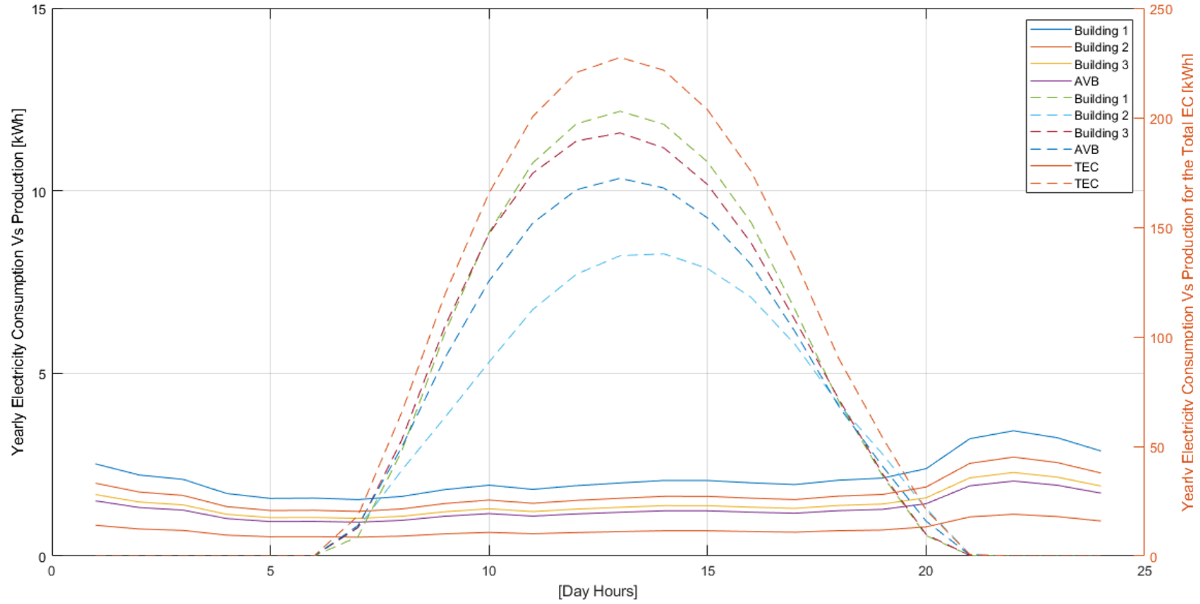

Figure 4.6: Daily Average Electricity Consumption and Production

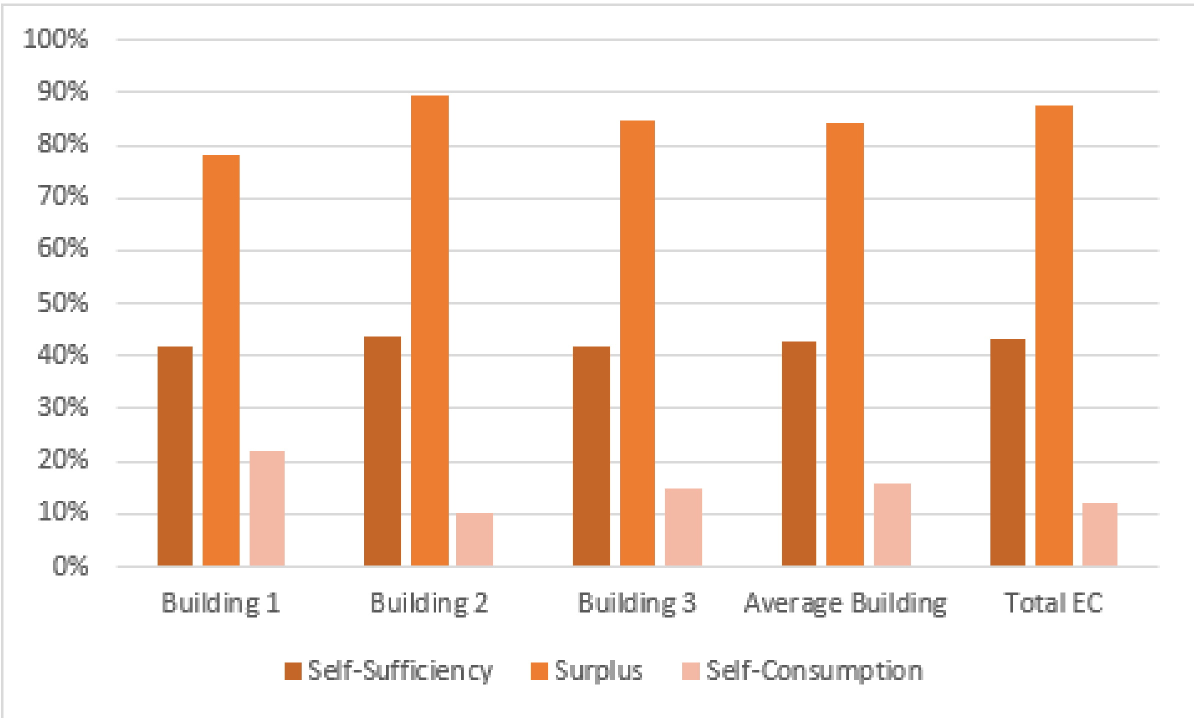

Figure 4.7: Electricity Self-Sufficiency and Surplus

For the Surplus, even though it varies a bit more, the values are still pretty similar once again due to how small the self-consumption is, compared to production, regardless of the number of apartments per building that in this city block is always quite small. These means that the PV system is overdimensioned when it comes to SC only, the produced electricity surpass by far the consumption needs.

The Total EC behaves similarly to the individual ECs, the difference being on the magnitude (right axis for the Total EC on Figure 4.6) of both the consumption and electricity production (with aggregated area). The latter could be used as *bargaining chip* to get better value for the surplus of electricity, however in this work that possibility it's not studied.

4.6.2 Case Study 2

Figure 4.8 shows the daily average electricity consumption and production for Building 1, AVB, and TEC for the second Case Study. One major difference that stands out immediately when compared to Case Study 1 is how the magnitude of electricity consumption is much closer to the magnitude of production, also to notice is that the consumption curves of the AVB and the Building 1 are the same. As can be seen on Figure 4.12, in this Case Study, the effective roof area per apartment is much smaller, meaning less produced electricity per apartment with a consumption that is similar, with a peak production of around 25 kWh and a peak consumption of around 20 kWh this PV System is much better dimensioned regarding SC.

This can also be seen in Figure 4.9. The surplus values are much smaller (around 50%) than the ones from the first case (around 80%) and the self-consumption is 3 times bigger for the AVB.

The self-sufficiency at around 35% for all cases is still fairly high. As can be seen on Figure 4.8, for a great part of the daily sunshine hours the electricity needs are satisfied with the one produced by the PV system.

The Total EC once again presents values that are similar to the individual EC cases.

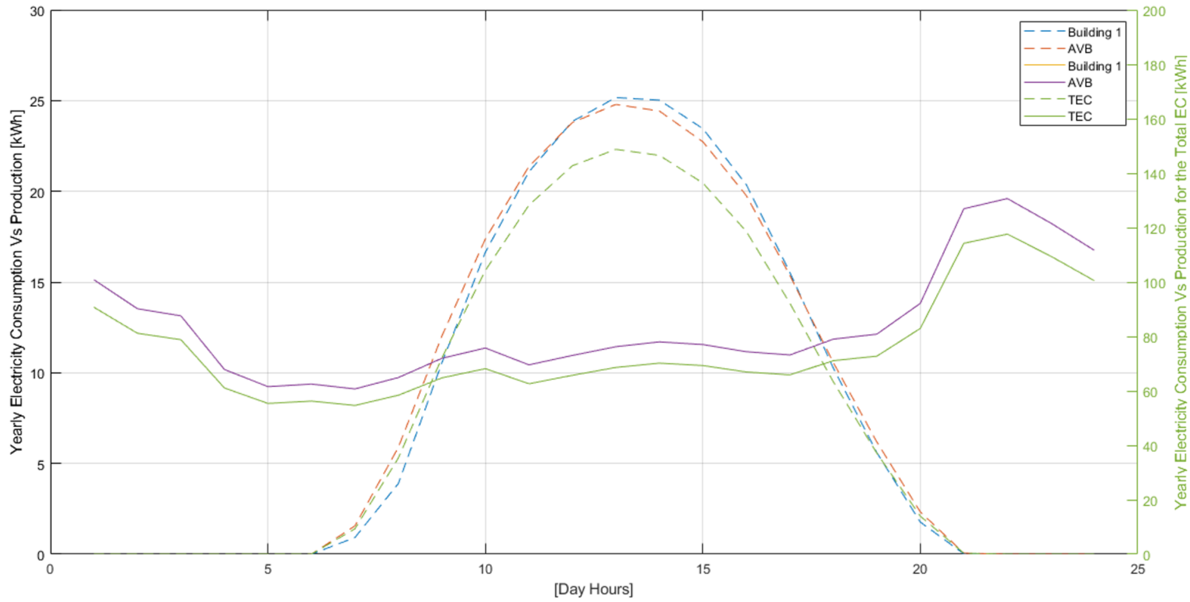

Figure 4.8: Daily Average Electricity Consumption vs Production

Figure 4.9: Self-Sufficiency, Surplus and Self-Consumption

4.6.3 Case Study 3

From Figure 4.10 it is possible to see how the consumption and production curves are similar in magnitude to the previous Case Study.

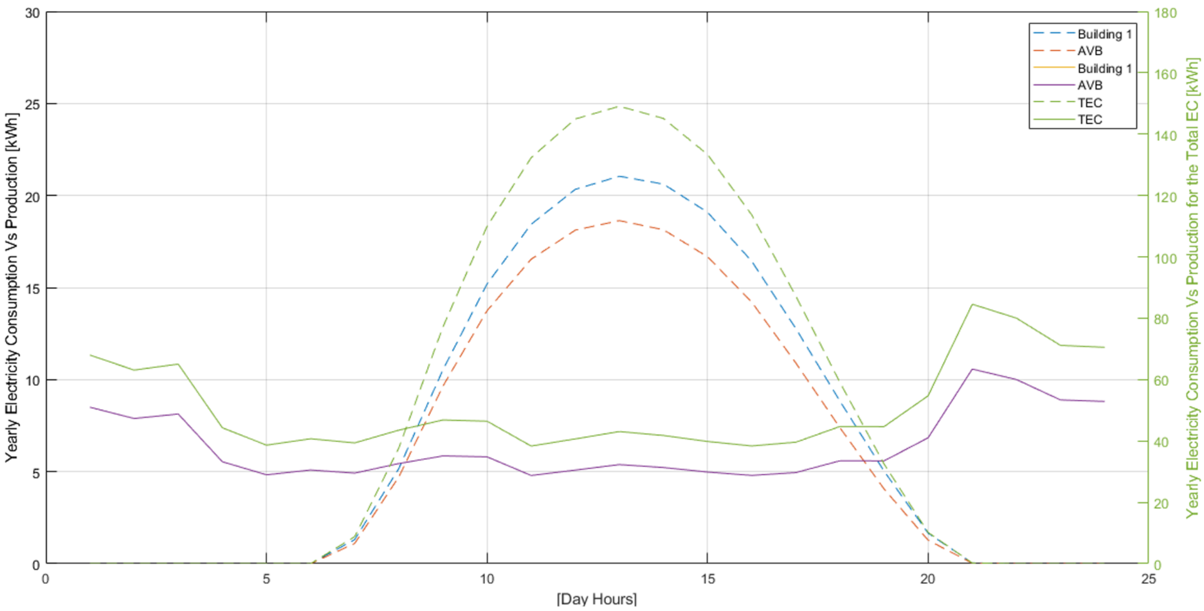

Figure 4.10: Daily Average Electricity Consumption vs Production

The amount of selected buildings is very close to Case Study 2, and with similar areas per roof (Figure 4.12). What most influences the Energy KPI's on this community is the difference in the amount of apartments per building. In this third case, the buildings having less than half the number of apartments and so half of the consumption.

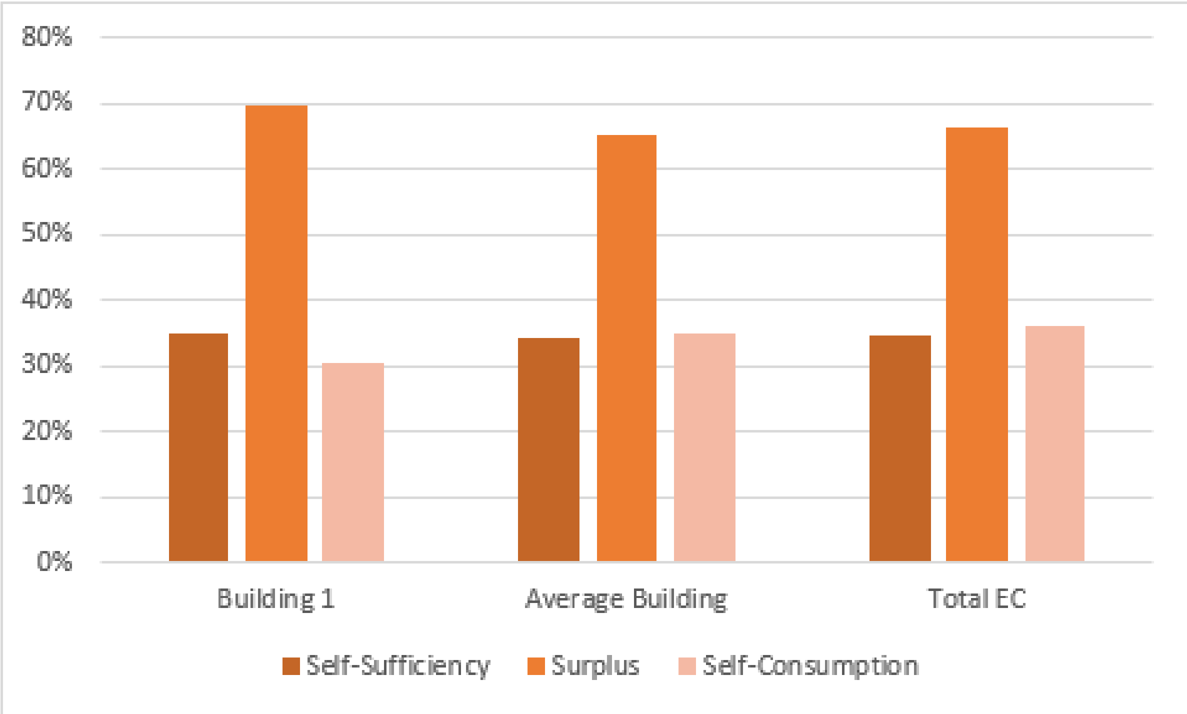

Figure 4.11: Percentage of Surplus, Self-Sufficiency and Self-Consumption

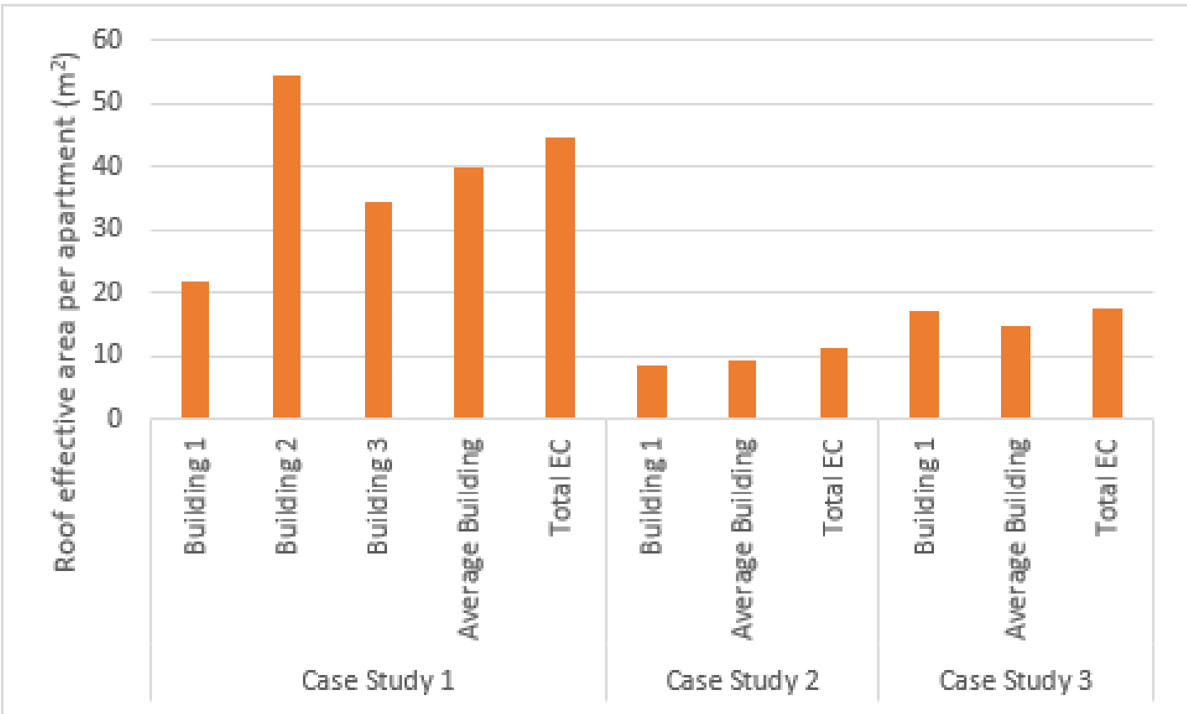

Figure 4.12: Effective Roof Area per Apartment

4.7 Financial Analysis

4.7.1 Tariff Analysis, Case Study 1

When it comes to the yearly electricity costs for Case Study 1 from Figure 4.13 the Dual Tariff regime is, in average, 36% lower than the Flat Tariff One. Such difference is explained by the cheaper price of electricity in the night period and the fact that during sunshine hours the electricity consumed is the one produced by the PV system as seen on Figure 4.6. The savings displayed on Figure 4.14 also confirm that a Dual Tariff is the most beneficial. For the other two Case Studies the same conclusion is also drawn, as can be seen on Appendix C.

It is also interesting to notice how Building 2 is the one with the least savings, a direct consequence from being the Building with the highest roof effective area per apartment. The lowest self-consumption creates the fewest yearly savings.

For the other two Case Studies the same conclusion are also drawn, and can be seen on Appendix C.

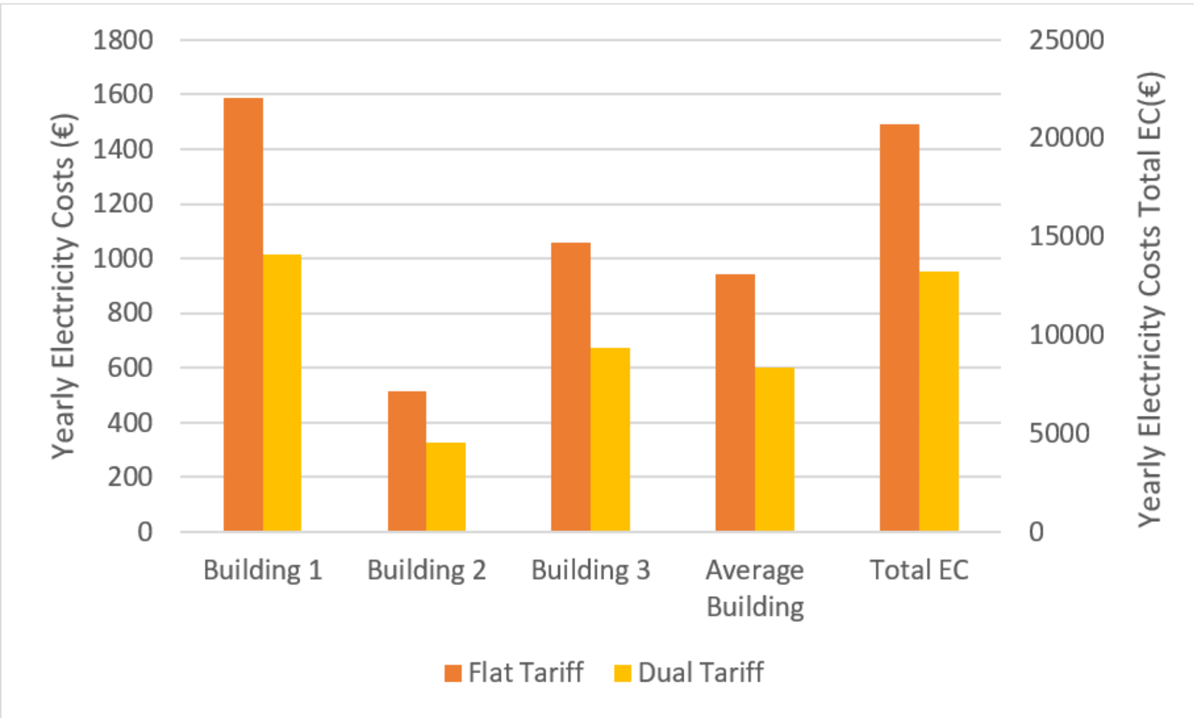

Figure 4.13: Costs with an EC

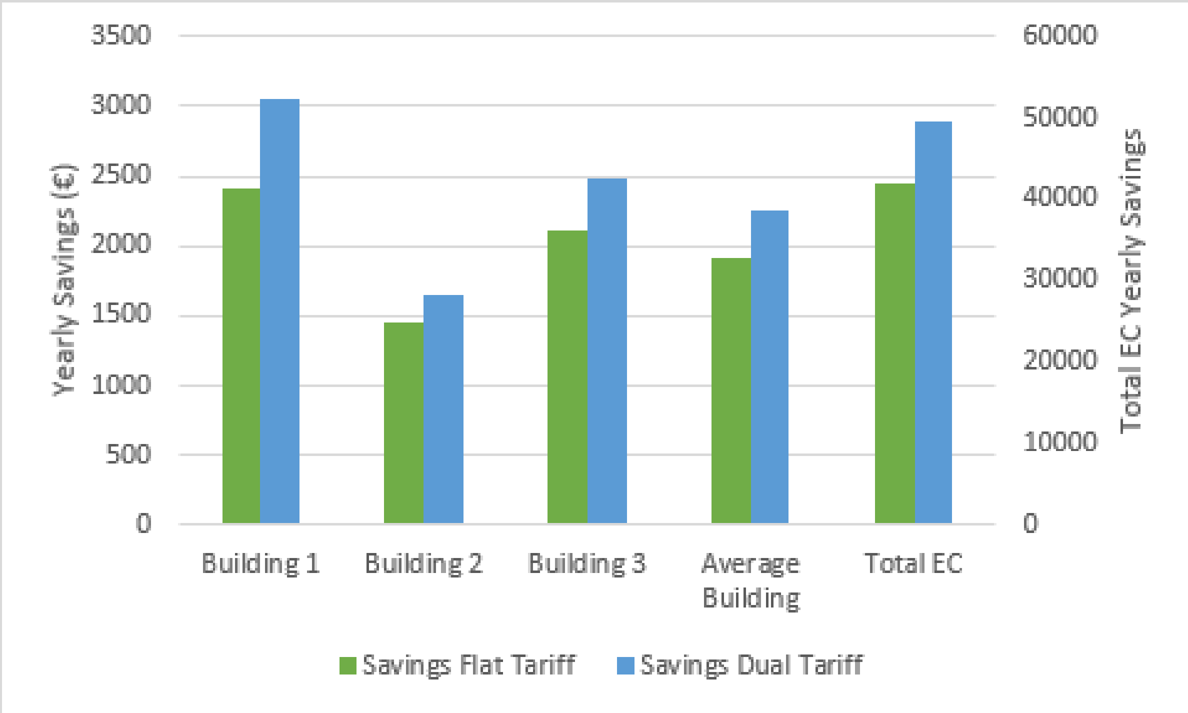

Figure 4.14: Savings with an EC

4.7.2 Discounted Payback Time

From Figure 4.15, Case Study 1, Building 2 has a DPBT far longer than the other ones. This happens because even though Investment Costs and Yearly Profits are fairly similar to the others buildings, the Yearly Savings are in average 30% smaller, extending the time it takes to payback the initial investment on the PV System.

With a DPBT below 10 years, Building 1 is the most attractive investment, a consequence of having the highest yearly savings.

To have in consideration is the fact that although it takes several years to payback the investment, after that the revenue from the high surplus of electricity continues to be quite high.

Major differences appear when comparing Case Study 1 and 2 average buildings, having a DPBT of 35 years in the first in comparison to 8 years on the latter. An EC using the total effective area is much better from the perspective of an investment in this neighbourhood where the buildings have a much larger amount of apartments and therefore smaller roof effective area per apartment. This can be even better seen on Figure 4.16 where the IRR is more attractive from an investment point of view.

Case Study 3 also presents interesting DPBTs, like in the second case study, the roof effective area per apartment is relatively small which reduces the investment costs and surplus, increasing the self consumption of electricity to the point of making it a good investment for all the cases. Also, one interesting thing is how the difference from having single building ECs or a Total EC is negligible, since the AVB and the TEC have similar values with the AVB being slightly better.

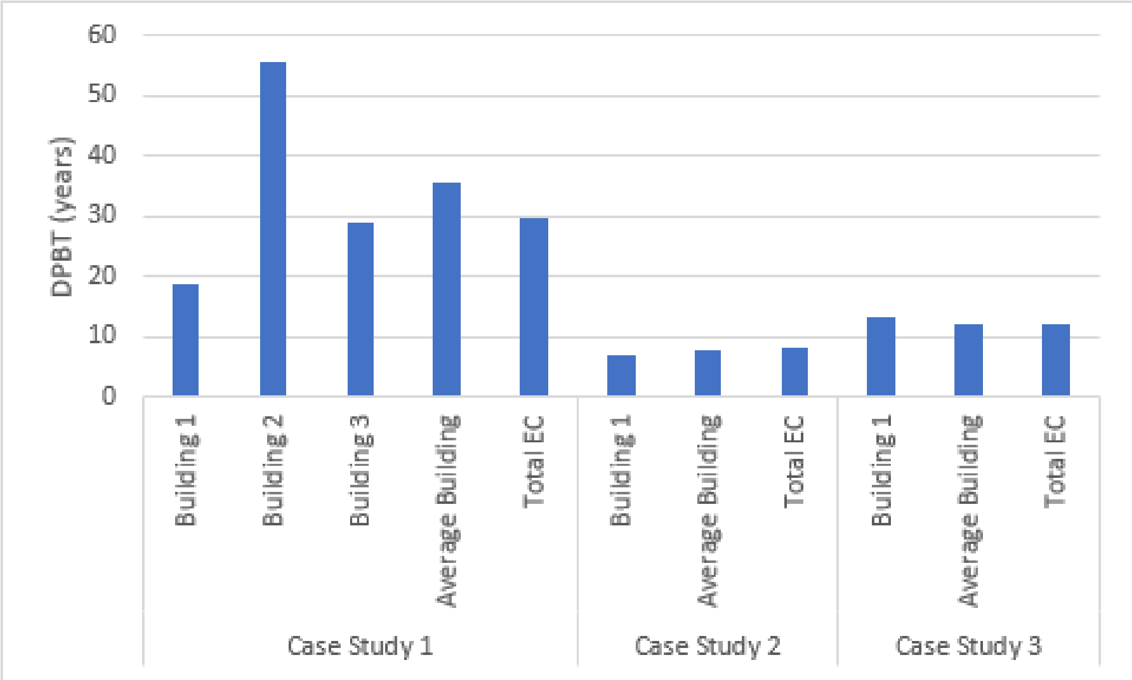

Figure 4.15: Discounted Payback Time

4.7.3 Internal Rate of Return

The IRR (for a 25 years period) being a complementary economic indicator to the DPBT shows the same conclusions. The first Case Study is by far the worst with IRR values for all cases smaller than 10%. Case 2 is the best one with IRRs of over 15% for all cases and the third Case is in-between the other ones.

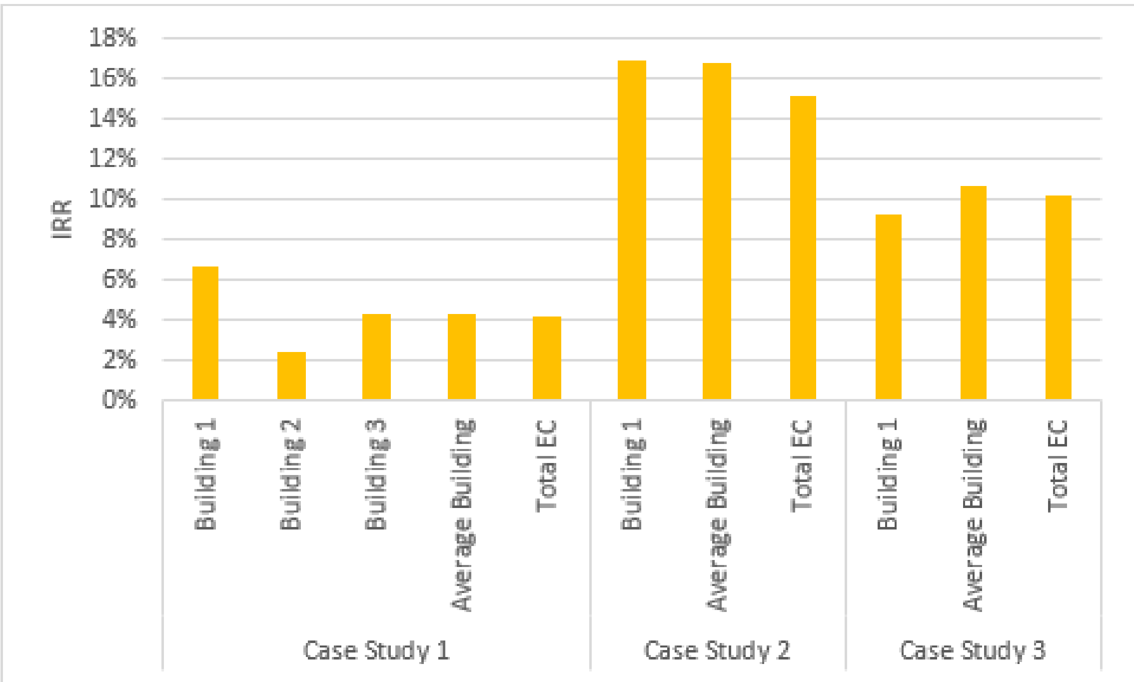

Figure 4.16: Internal Rate of Return

4.8 CO2 Emissions

Figure 4.17 showcases the positive environmental impact of ECs, for the average building of each case study. For Case Study 1, the yearly CO2 emissions decrease to almost half (a reduction of 43%) of the ones in a scenario without an EC, almost reaching the 55% EU meta for 2030. However, it is not the best case from a financial perspective. The other two case studies, not having such a high amount of reduced CO2 emissions, still make good progress in trying to achieve the 55% goal: for Case Study 2 a reduction of 35% and for Case Study 3 34%, validating the importance of this type of solution when it comes to the achieving a carbon neutral and more sustainable future. However, given the different electricity demand scales of the case studies, in absolute terms (kg) Case study 2 and 3 contribute much more to decarbonization of urban environment.

The avoided CO2 emissions from the surplus of electricity sold to the grid in the ECs isn't accounted for in here, meaning that even though it doesn't show on Figure 4.17 there are emissions that will be avoided on the place where this surplus of electricity is consumed.

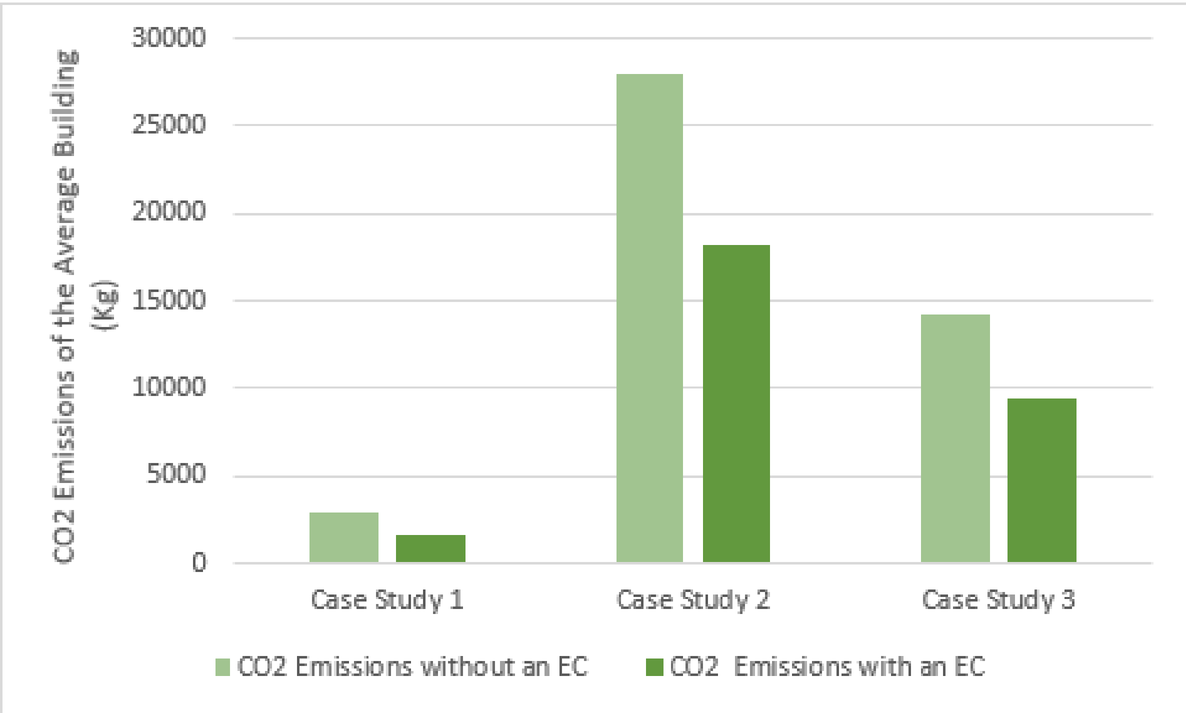

Figure 4.17: Yearly CO2 Emissions for the average building of each Case Study

4.9 Net Zero Energy Building

4.9.1 Case Study 1

As seen above by using all the available effective roof area, the PV System is over-dimensioned for self-consumption causing the DPBTs to be too long and the IRRs too low. Therefore, an analysis was made to encounter the amount of effective area to be used in an EC in order to attain a Net Zero Energy Building, which produces the same amount of electricity that consumes. This corresponds to a balance between self-consumption and self-sufficiency that leads to a proper dimensioning of the PV System when wanting the PV production to be the same as the yearly electricity consumption needs and not overshooting that value.

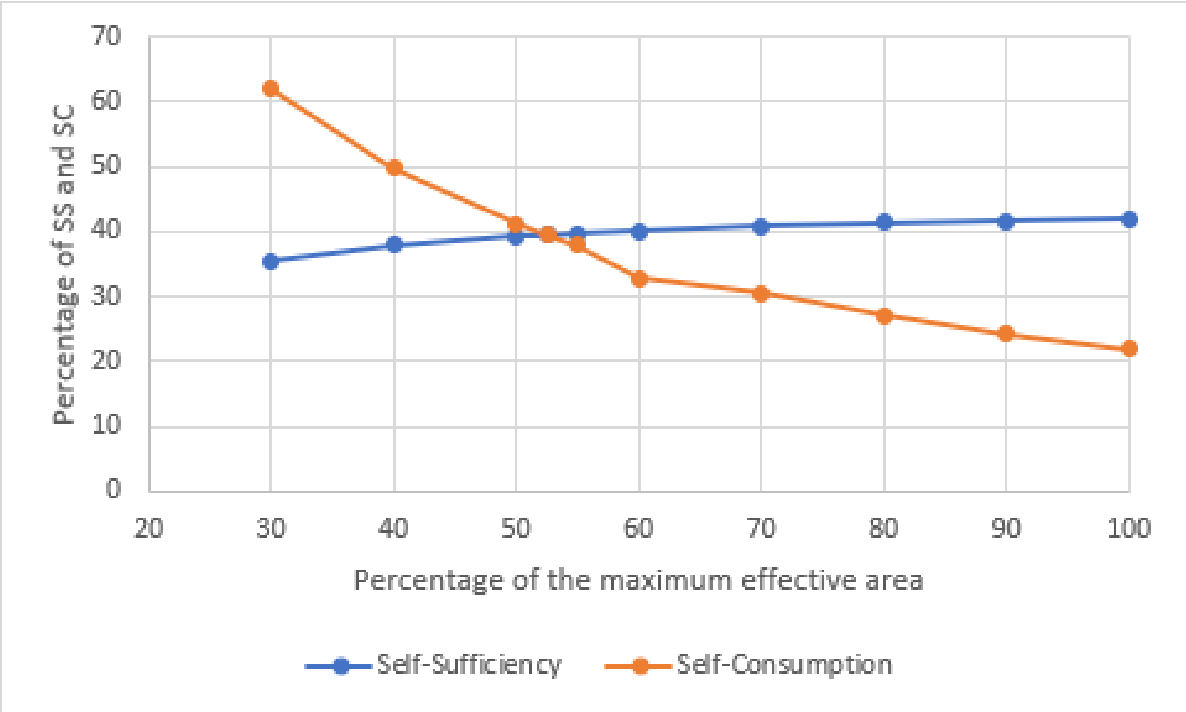

Figure 4.18: Change on SS and SC with the percentage of maximum effective area for the installation of a PV System in Building 1

In Figure 4.18, the percentage of the effective area is progressively diminished from the max down to 30%, and at 52% the values of self-sufficiency and self-consumption match and the point of the NZEB is found. This really showcases the potential of a PV self-consumption EC, the yearly consumption needs of a building can not only be obtained but also surpassed.

As for the changes in the KPIs, Table 4.9 summarizes them. For all the Buildings and the TEC scenario the changes are remarkable: the DPBT is way smaller and consequently the IRR way higher, this comes due to the large reduction in the initial investment to have the NZEB scenario which does not translate in a reduction of the savings at the same proportion. Even though, for example in the case of Building 3, the initial investment is reduced in 60% the savings only reduce in 40%, once again a reflection on the smaller price that the surplus electricity is sold to grid in comparison to the price for which it is bought.

Table 4.9: NZEB and Max effective area Case Study 1 KPIs comparison

Building:	1		2		3		AVB		TEC	
Effective Area:	Max	NZEB	Max	NZEB	Max	NZEB	Max	NZEB	Max	NZEB
Investment (€):	38740	21544	32354	8557	40093	15688	36671	14434	806764	315495
Nº of Solar Panels:	78	41	64	15	81	29	73	26	1626	582
SC (%):	22	39.5	10.4	40	15.1	39	15.9	39	15.3	40
SS (%):	41.9		43.6		42		42.7		43	
Savings (€):	3043	2190	1644	734	2485	1447	2250	1320	49504	28875
DPBT (years):	18.8	11.9	55.6	15.57	28.9	13.9	35.54	16	29.7	14
IRR (%):	6.7	10	2.4	8	4.3	9	4.3	9	4.2	8.8

4.9.2 Case Study 2

For the Second Case, the NZEB is impossible to obtain as can be seen of Figure 4.19 for Building 1, with the much larger amount of electricity consumption per Building even when the full effective roof area is occupied with solar panels the produced electricity is not enough to equalize the consumption needs in a year.

The best scenario is the one already discussed in Section 4.7 where all of the roof effective area is used.

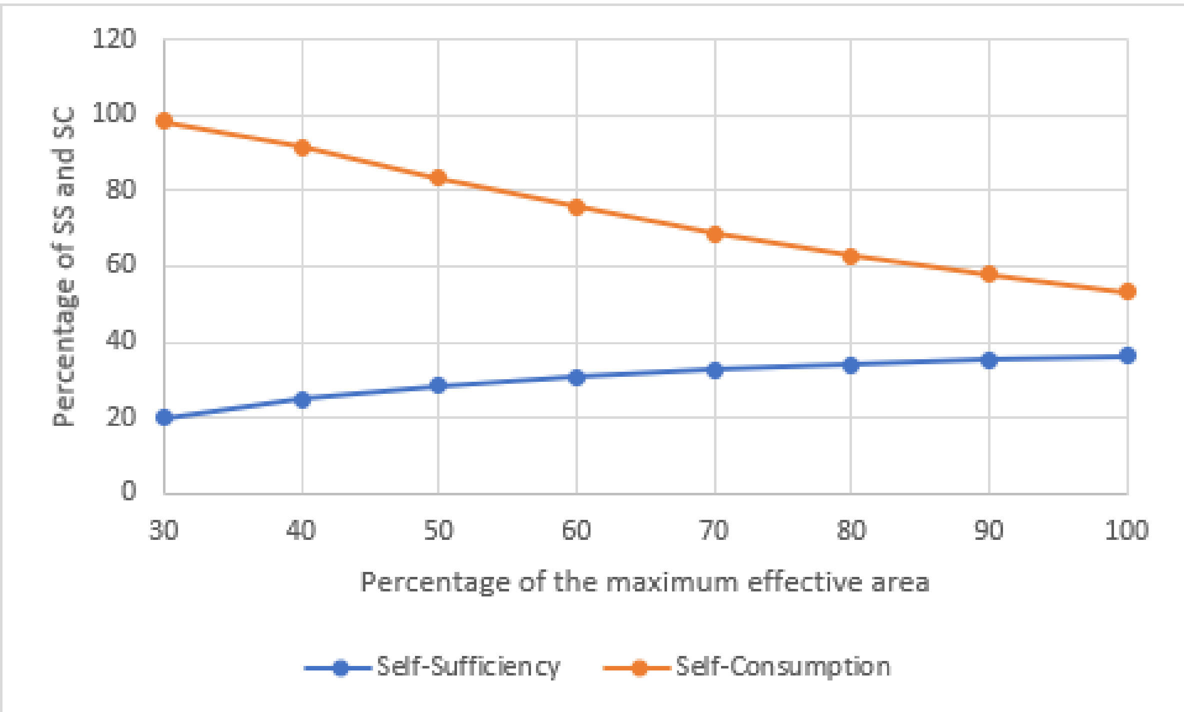

Figure 4.19: Change on SS and SC with the percentage of maximum effective area for the installation of a PV System in Building 1

4.9.3 Case Study 3

Regarding the third Case Study, Building 1 (Figure 4.11) is the only case where the NZEB can be obtained at 90% of the maximum effective area, as can be seen on Figure 4.20. With just a slightly difference in the effective roof of 10% the difference in the KPIs is small, only with a decrease of a year in the DPBT and increase of 0.9% in the IRR.

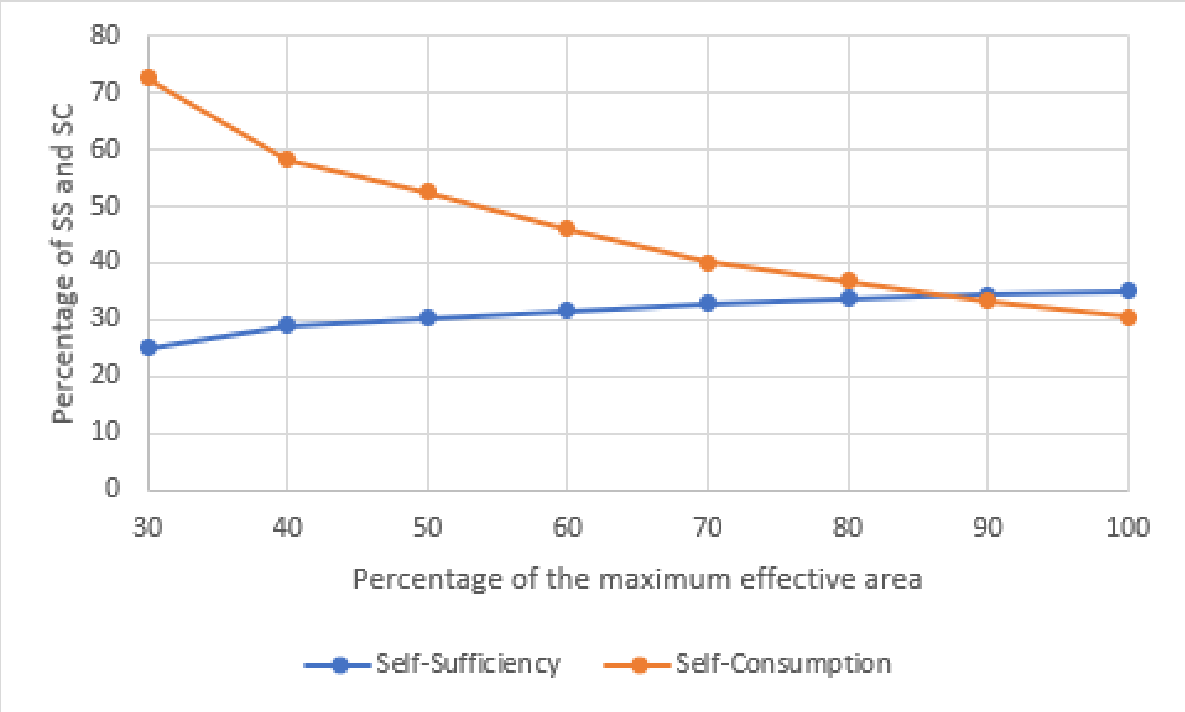

Figure 4.20: Change on SS and SC with the percentage of maximum effective area for the installation of a PV System in Building 1

Table 4.10: NZEB and Max effective area Case Study 3 KPIs comparison

Building	**1**	
Effective Max Area (%):	**Max**	**NZEB**
Investment (€):	71374	63306
Nº of Solar Panels:	153	134
SC (%):	30.5	34
SS (%):	35	
Savings (€):	6748	6379
DPBT (years):	13.3	12.1
IRR (%):	9.3	10.2

4.9.4 Comparison With the Literature

The approach used on this work of developing an algorithm capable of doing the analyses of the potential of a self-consumption EC in any desired location of Lisbon is innovative, as most of the available literature is on the analysis of specific buildings or neighbourhoods.

On [44] the focus is the Portuguese residential electricity consumption, the top-down portion of the analysis uses data aggregated by municipality for the year 2001, while the bottom-up portion uses the most recent Portuguese consumer expenditure survey from 2005 and 2006 [44]. The results of the last one show an average yearly consumption of electricity per capita of 1432 kWh in the city of Lisbon. In this work for the three case studies the values found for this metric in the average building are respectively: 1283, 1337 and 1271 (kWh/year/capita). The results are in the same order of magnitude, with a maximum difference of just 11% in the third case study.

In the case of study [22], the authors used Energy Plus and Matlab to evaluate the use of solar energy and retrofit measures in obtaining net zero energy buildings and optimal ECs through shared consumption of four buildings. When considering the NZEB scenario they found a reduction of 42% in CO2 emissions and a SC of 43% which is similar and inline with values found for the Case Studies analysed on this work. In Chapter 4.6 the self-consumption ranges from a minimum of 10% in Case Study 1 to a maximum 52% in the second, and when considering the NZEB scenario on Chapter 4.9 that value goes to a max of 39% on Case Study 1 and a minimum of 34% in the third one.

The calculation of the NZEB shows how the available effective roof area influences the performance of ECs. For buildings with an high roof effective area per apartment the PV system will be overdimensioned when using all the area and the best scenario is to opt for the NZEB scenario where just part of that area is used, like on Case Study 1. On the other hand, when that effective roof area per apartment is smaller the available roof area might not even be enough to obtain the NZEB such is the case of Case Study 2. In the paper [23], C.H Villar et al, designs a PV System to maximize the self-consumption for each of the consumption profiles already discussed in chapter 3.1.4. For those three scenarios the self-consumption ranges from a maximum of 99% to a minimum of 93% and self-efficiencies of 8% to 20%, which results of on DPBTs of 5 years to 8 years, and IRRs of 9% to 17%. In comparison, the values found for this thesis in Table 4.9 are somewhat different, the closest scneario is the NZEB where the self-consumption, being much higher than the base scenario, at around 40% still are much smaller than the ones considered by C.H Villar et al but are however similar to the ones found by Diana et al in [24] on their high solar fraction scenario.

Chapter 5

Conclusions

5.1 Main Conclusions and Achievements

With the goal of being able to assess the potential of self-consumption Energy Communities in the city of Lisbon, a MATLAB tool was developed to capture with high spatial resolution the influential variables of an EC. The final goal is to allow anyone, just trough the insertion of geographical coordinates, to obtain an accurate estimation of the PV potential and electricity consumption needs of any desired location in the city. This capacity is particular useful to rapidly pre-assess the potential benefits (or not) of joining/creating an EC in that location.

After the validation of the solar production, the desired outputs for the tool were achieved which allowed its testing on three neighbourhoods with different building typologies and occupancy profiles, in order to evaluate the produced results.

The implementation of ECs proved to be, not only from a financial perspective, but also environmentally, a good decision. A significant decrease on CO2 emissions (ranging from 35% to 43%) is observed in all three Case Studies, allowing a step further towards carbon neutrality, as envisioned by the EU.

Another interesting outcome regards the usage of all the roof area to install a PV System. Due to the low OMIE price for which surplus electricity can be sold to the grid, having a large installation compared to the consumption needs is a bad financial decision, given the low grid injection tariff. This is better shown by the effective roof area apartment ratio, in Case Study 1 where this ratio is high for buildings where the ECs perform poorly financially, looking into the second Case Study the ratio is 75% smaller, for the average building, which translates on a much better financial performance, with lower DPBTs and higher IRRs. Consequently, reducing the PV array size to obtain a NZEB proved to be the better financial decision, denoting better DPBT and IRRs.

Additionally, the results enabled observing that the differences between single building ECs and the Total EC are almost negligible, with the only difference superior to 10% occurring for the DPBT in Case Study 1 (14%), when considering the same electricity tariffs, such is the case of this work.

5.2 Limitations of the MATLAB Tool

The developed toolbox, despite presenting an accurate depiction of the reality of self-consumption ECs in the city of Lisbon, has some limitations due to some of the simplifications that had to be made. One is related to the fact that only three different family profiles where considered, which is far from the dozens of different inhabitants configurations of the apartments in Lisbon.

To select the desired location of study one needs to use an external GIS software such as Google Earth the obtain the geographic coordinates of said place.

Furthermore, the considered solar radiation model doesn't take into account shadowing, which in a city full of buildings with different heights, side by side, could in some cases translate into an overestimation of the yearly incident radiation.

5.3 Future Work

Throughout the development of the MATLAB tool some opportunities to further develop and improve the tool were identified and are listed below:

- Optimize the code, improving the computational speed of the tool.
- Consider peer-to-peer energy trading to better optimize the usage of surplus electricity.
- Build a graphic interface to facilitate and improve the usability of the tool.
- Utilize more electricity consumption profiles to better estimate the needs of each building.
- Improve the solar radiation model to include shadowing effects.

Bibliography

[1] United nations department of economic and social affairs. URL https://www.un.org/development/desa/en/news/population/2018-revision-of-world-urbanization-prospects.html. accessed 15 October 2021.

[2] A european green deal — european commission. URL https://ec.europa.eu/info/strategy/priorities-2019-2024/european-green-deal_en. accessed 15 October 2021.

[3] Fit for 55 — legislative train schedule — european parliament. URL https://www.europarl.europa.eu/legislative-train/theme-a-european-green-deal/package-fit-for-55. accessed 15 October 2021.

[4] A. Caramizaru. Energy communities: an overview of energy and social innovation. 2020. URL https://ec.europa.eu/jrc. accessed 20 September 2021.

[5] M. Altmann, A. Brenninkmeijer, J.-C. Lanoix, D. Ellison, A. Crisan, A. Hugyecz, G. Koreneff, and S. Hänninen. Decentralized energy systems. 2010.

[6] D. P. Kaundinya, P. Balachandra, and N. H. Ravindranath. Grid-connected versus stand-alone energy systems for decentralized power-a review of literature, 10 2009.

[7] Decentralised energy futures: The changing emissions reduction landscape. volume 29, pages 138–143. Elsevier B.V., 2015.

[8] S. Freitas, C. Catita, P. Redweik, and M. C. Brito. Modelling solar potential in the urban environment: State-of-the-art review, 2015.

[9] Usgs.gov — science for a changing world, . URL https://www.usgs.gov/. accessed 15 August 2021.

[10] Dem, dsm & dtm differences - a look at elevation models in gis - gis geography, . URL https://gisgeography.com/dem-dsm-dtm-differences/. accessed 15 August 2021.

[11] J. Hofierka and M. Šúri. Proceedings of the open source gis-grass users conference, 2002. URL http://www.geomodel.sk.

[12] A comparative evaluation of photovoltaic electricity production assessment software (pvgis, pvwatts and retscreen). volume 2, pages S175–S189. Springer Basel, 11 2015.

[13] Photovoltaic geographical information system (pvgis) — eu science hub. URL https://ec.europa.eu/jrc/en/pvgis. accessed 20 September 2021.

[14] Pvwatts calculator. URL https://pvwatts.nrel.gov/pvwatts.php. accessed 12 June 2021.

[15] Directorate general for internal policies policy department a: Economic and scientific policy pe 440.280 en, 2010.

[16] Distributed generation of electricity and its environmental impacts — us epa. URL https://www.epa.gov/energy/distributed-generation-electricity-and-its-environmental-impacts. accessed 15 September 2021.

[17] Renewable energy – recast to 2030 (red ii) — eu science hub. URL https://ec.europa.eu/jrc/en/jec/renewable-energy-recast-2030-red-ii. accessed 26 September 2021.

[18] Clean energy for all europeans package — energy. URL https://ec.europa.eu/energy/topics/energy-strategy/clean-energy-all-europeans_en. accessed 29 of October 2021.

[19] G. P. Luz and R. A. E. Silva. Modeling energy communities with collective photovoltaic self-consumption: Synergies between a small city and a winery in portugal. *Energies*, 14, 1 2021.

[20] Solar resource maps and gis data for 200+ countries — solargis. URL https://solargis.com/maps-and-gis-data/download/europe. accessed 20 October 2021.

[21] S. Ramos, Z. Foroozandeh, J. Soares, I. Tavares, P. Faria, and Z. Vale. Shared pv production in energy communities and buildings context. *Renewable Energy and Power Quality Journal*, 19: 459–464, 9 2021.

[22] F. Ascione, D. F. Napolitano, N. Bianco, G. P. Vanoli, and G. M. Mauro. Optimization of solar energy exploitation for a neighborhood towards nearly zero energy buildings.

[23] C. H. Villar, D. Neves, and C. A. Silva. Solar pv self-consumption: An analysis of influencing indicators in the portuguese context. *Energy strategy reviews*, 18:224–234, 2017.

[24] D. Neves, I. Scott, and C. A. Silva. Peer-to-peer energy trading potential: An assessment for the residential sector under different technology and tariff availabilities. *Energy*, 205, 8 2020.

[25] A. Alhamwi, W. Medjroubi, T. Vogt, and C. Agert. Gis-based urban energy systems models and tools: Introducing a model for the optimisation of flexibilisation technologies in urban areas. *Applied Energy*, 191:1–9, 2017.

[26] Y. wei Sun, A. Hof, R. Wang, J. Liu, Y. jie Lin, and D. wei Yang. Gis-based approach for potential analysis of solar pv generation at the regional scale: A case study of fujian province. *Energy Policy*, 58:248–259, 7 2013.

[27] Homepage - lisboa e-nova - agência de energia-ambiente de lisboa. URL https://lisboaenova.org/en/homepage-en/. accessed 16 September 2021.

[28] F. Hebeler. Dept. of geography, university zurich. 2008.

[29] S. A. M. Maleki, H. Hizam, and C. Gomes. Estimation of hourly, daily and monthly global solar radiation on inclined surfaces: Models re-visited. *Energies*, 10, 2017.

[30] L. Kumar, A. K. Skidmore, and E. Knowles. Modelling topographic variation in solar radiation in a gis environment. *International Journal of Geographical Information Science*, 11:475–497, 1997.

[31] G. Wypych. Measurements in assessment of weathering conditions. *Handbook of Material Weathering*, pages 93–108, 2018.

[32] Solar radiation cloud cover adjustment calculator. URL `http://www.shodor.org/os411/courses/_master/tools/calculators/solarrad/`. accessed 19 September 2021.

[33] Renewables.ninja. URL `https://www.renewables.ninja/`. accessed 20 June 2021.

[34] Iniciativa Energia - Instituto Superior Técnico, "O futuro do solar em Portugal: que desafios e que oportunidades? "Proj. OTGEN EDP-Produção. Reference to a report.

[35] Instituto nacional de estatística. URL `http://mapas.ine.pt/download/index2011.phtml`. accessed 21 September 2021.

[36] Cerâmica torreense. URL `https://www.ceramicatorreense.pt/en/`. accessed 18 September 2021.

[37] P. Berens. Circstat: A matlab toolbox for circular statistics. *Journal of Statistical Software*, 31(1), 2009.

[38] Project sunroof. URL `https://sunroof.withgoogle.com/`. accessed 14 July 2021.

[39] Macolis - climatização e sistemas de conforto. URL `https://www.macolis.pt/`. accessed 20 September 2021.

[40] K. D. Syahindra, S. Ma'Arif, A. A. Widayat, A. F. Fauzi, and E. A. Setiawan. Solar pv system performance ratio evaluation for electric vehicles charging stations in transit oriented development (tod) areas. volume 231. EDP Sciences, 1 2021.

[41] R. Luthander, J. Widén, D. Nilsson, and J. Palm. Photovoltaic self-consumption in buildings: A review, 3 2015.

[42] Tarifários de eletricidade e gás natural para particulares — edp. URL `https://www.edp.pt/particulares/energia/tarifarios/`. accessed 15 September 2021.

[43] M. Despotovic, V. Nedic, D. Despotovic, and S. Cvetanovic. Review and statistical analysis of different global solar radiation sunshine models, 12 2015.

[44] D. Wiesmann, I. L. Azevedo, P. Ferrão, and J. E. Fernández. Residential electricity consumption in portugal: Findings from top-down and bottom-up models. *Energy Policy*, 39:2772–2779, 5 2011.

Appendix A

Roof Sections Orientation, Inclination and Yearly Solar Radiation

A.1 Case Study 2

Table A.1: Roof Sections Orientation and Inclination before and after the threshold for minimum incident yearly solar radiation

Building:	Roof Section Orientation (°):				Roof Section Inclination (°):			
	North	East	South	West	North	East	South	West
1	322.7	49.4	146.5	237.1	21.4	23.42	21.3	20.60
			146.5	237.1		23.42		20.60

Table A.2: Roof Sections yearly incident solar radiation before and after the threshold for the minimum accepted value

Building:	Roof Section Yearly Incident Solar Radiation (kWh/m2/year):			
	North	East	South	West
1	1354.5	1382.8	1888.9	1806.0
			1888.9	1806.0

A.2 Case Study 3

Table A.3: Roof Orientation and Inclination before and after the threshold for minimum yearly radiation is applied

Building:	Roof Section Orientation (°):				Roof Section Inclination (°):			
	North	East	South	West	North	East	South	West
1	343.7	90.6	176	274.9	18.4	12.5	17.2	11
		90.6	176	274.9		12.5	17.2	11

Table A.4: Roof Sections yearly incident solar radiation before and after the threshold for the minimum accepted value

Building:	**Roof Section Yearly Incident Solar Radiation (kWh/m2/year):**			
	North	**East**	**South**	**West**
1	1350.3	1673.0	1899.1	1658.5
		1673.0	1899.1	1658.5

Appendix B

Roof Area and Radiation

B.1 Case Study 2

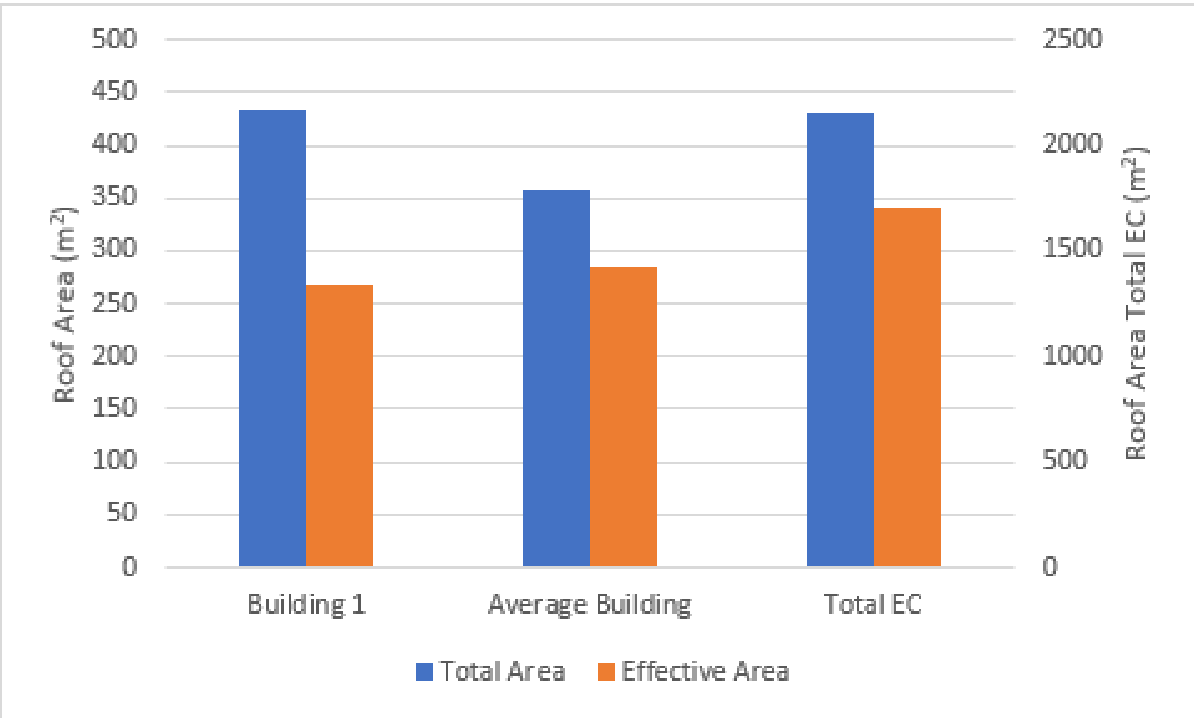

Figure B.1: Total Roof Area vs the Effective Area

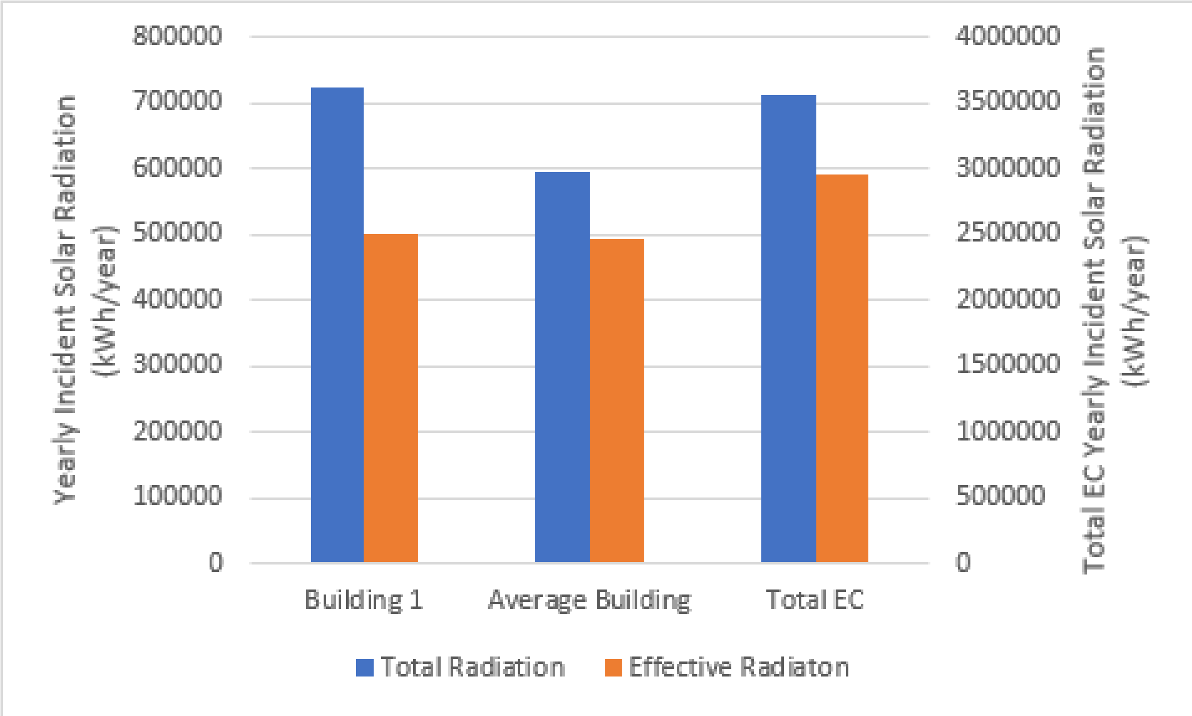

Figure B.2: Total and Effective Roof Yearly Incident Radiation

B.2 Case Study 3

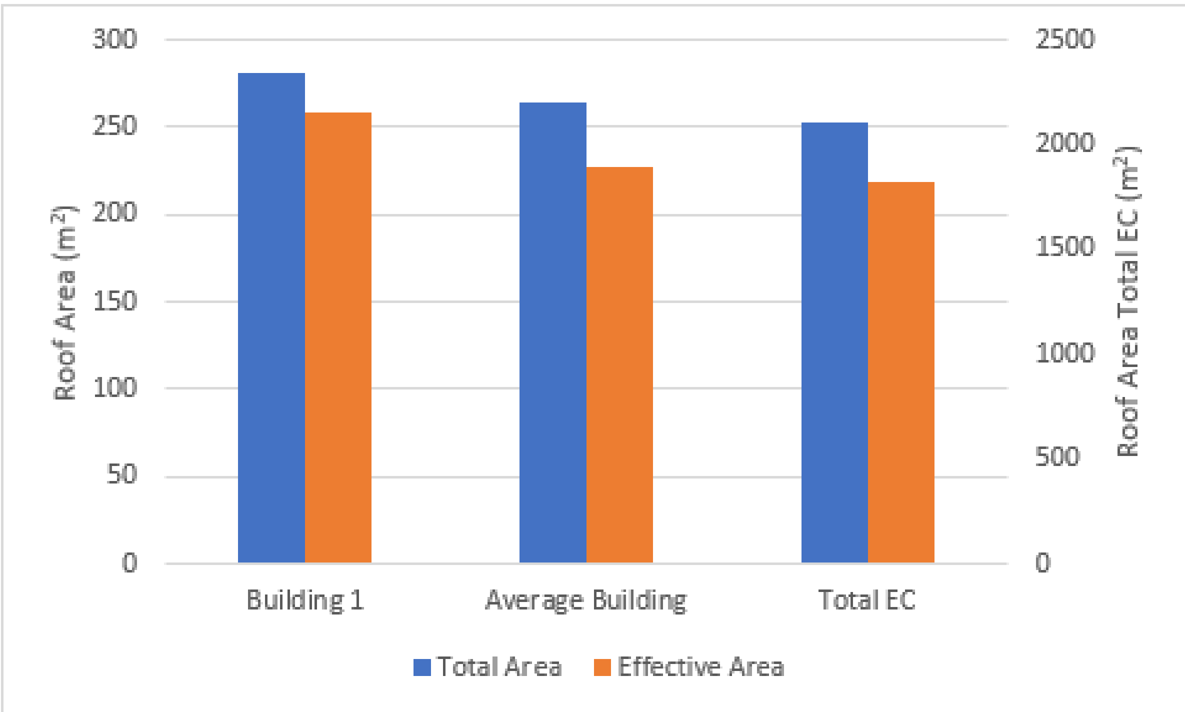

Figure B.3: Total Roof Area vs the Effective Area

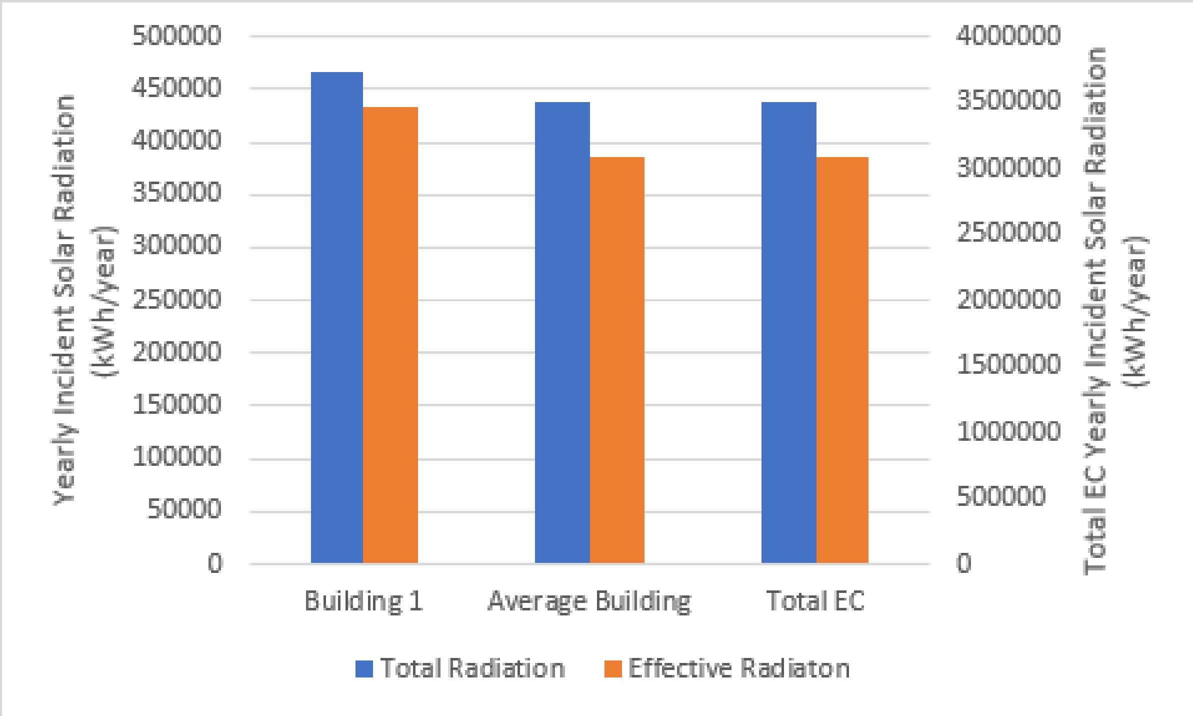

Figure B.4: Total and Effective Roof Yearly Incident Radiation

Appendix C

Tariff Analyses

C.1 Case Study 2

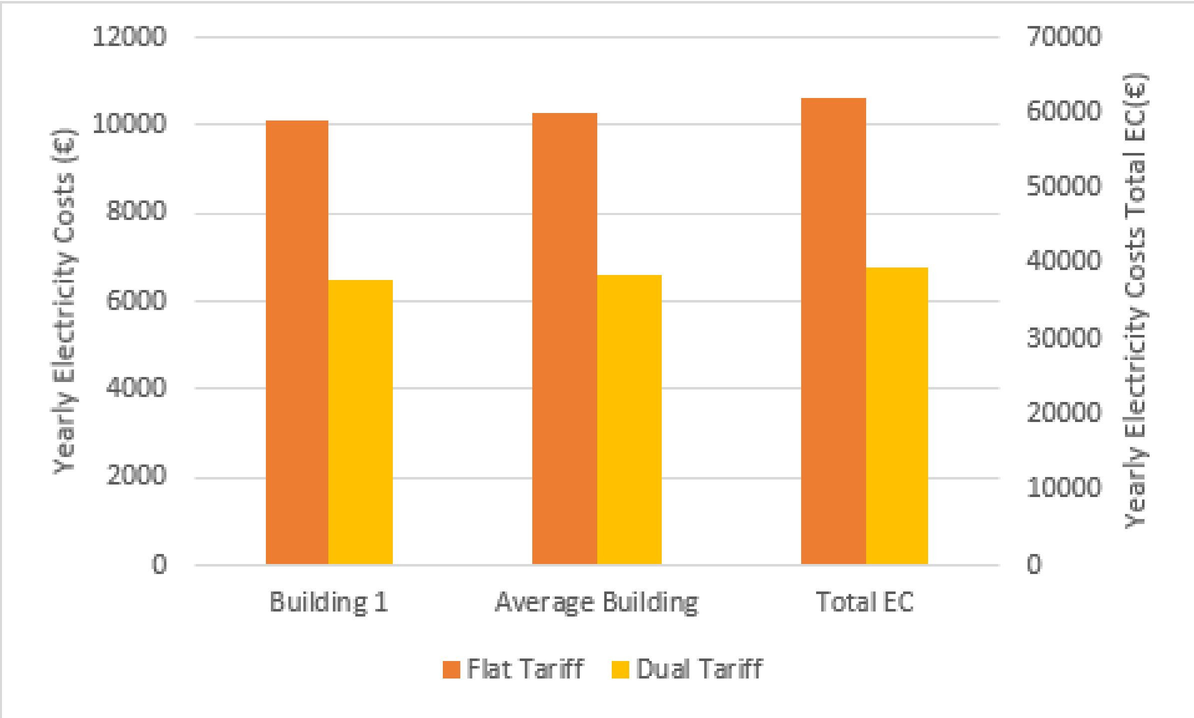

Figure C.1: Costs of having an EC

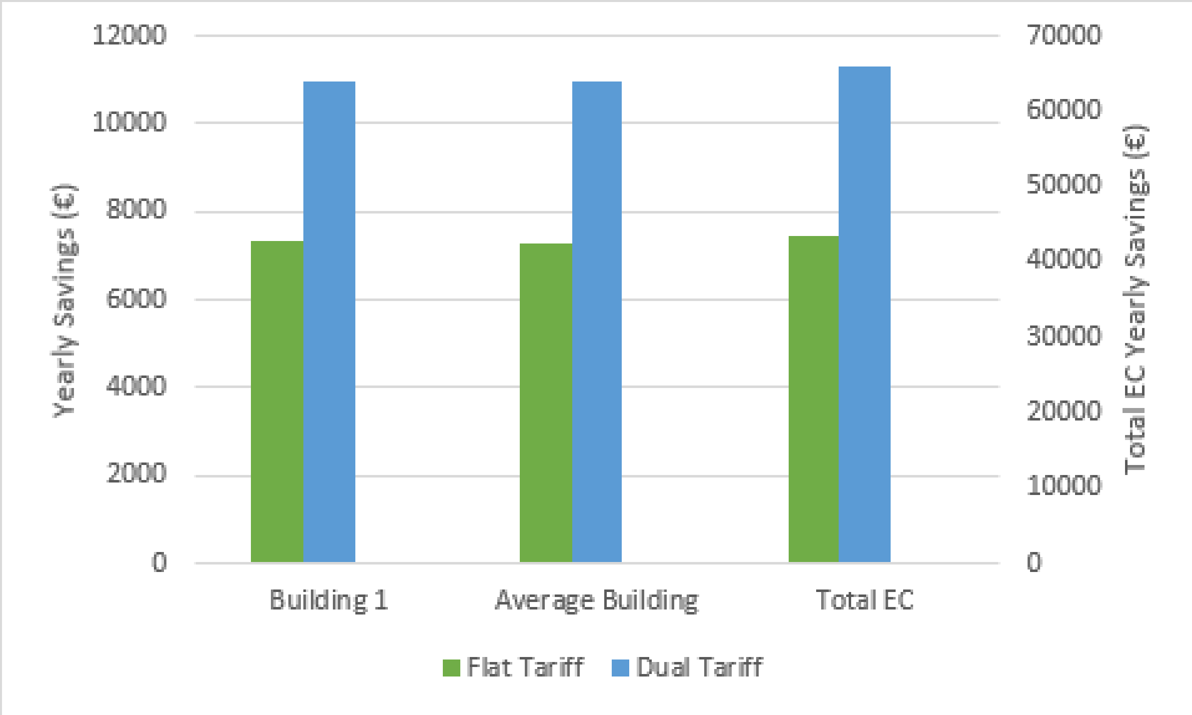

Figure C.2: Savings of having an EC

C.2 Case Study 3

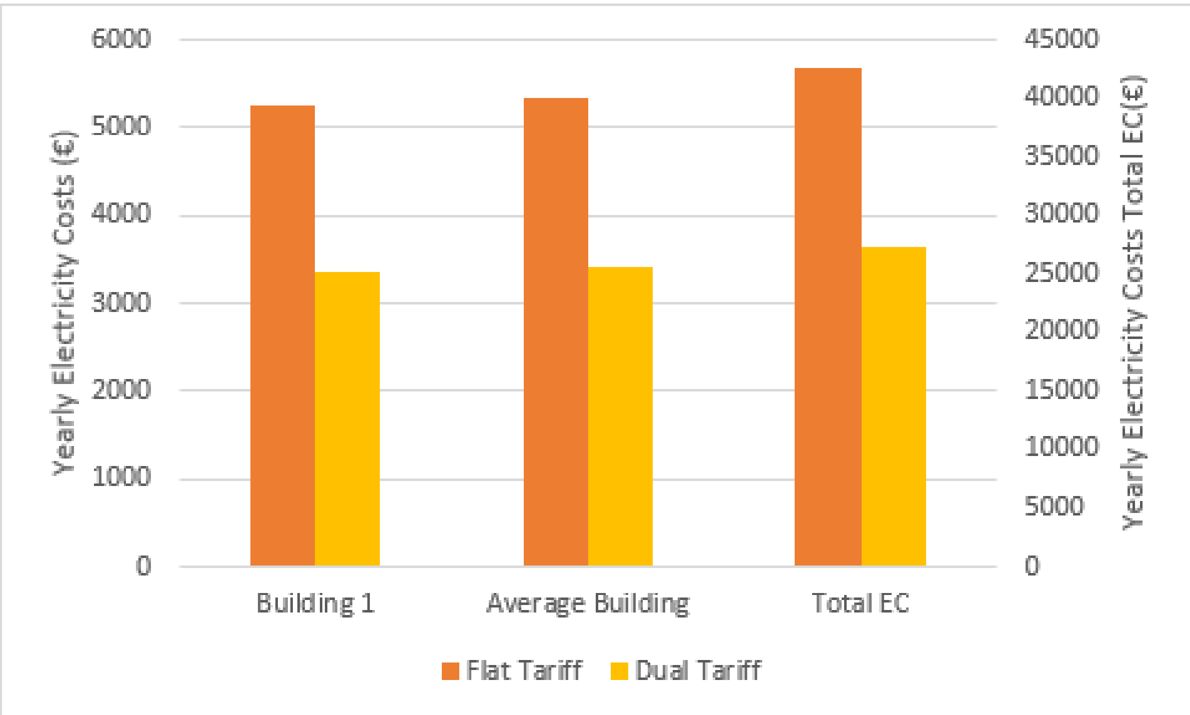

Figure C.3: Costs of having an EC

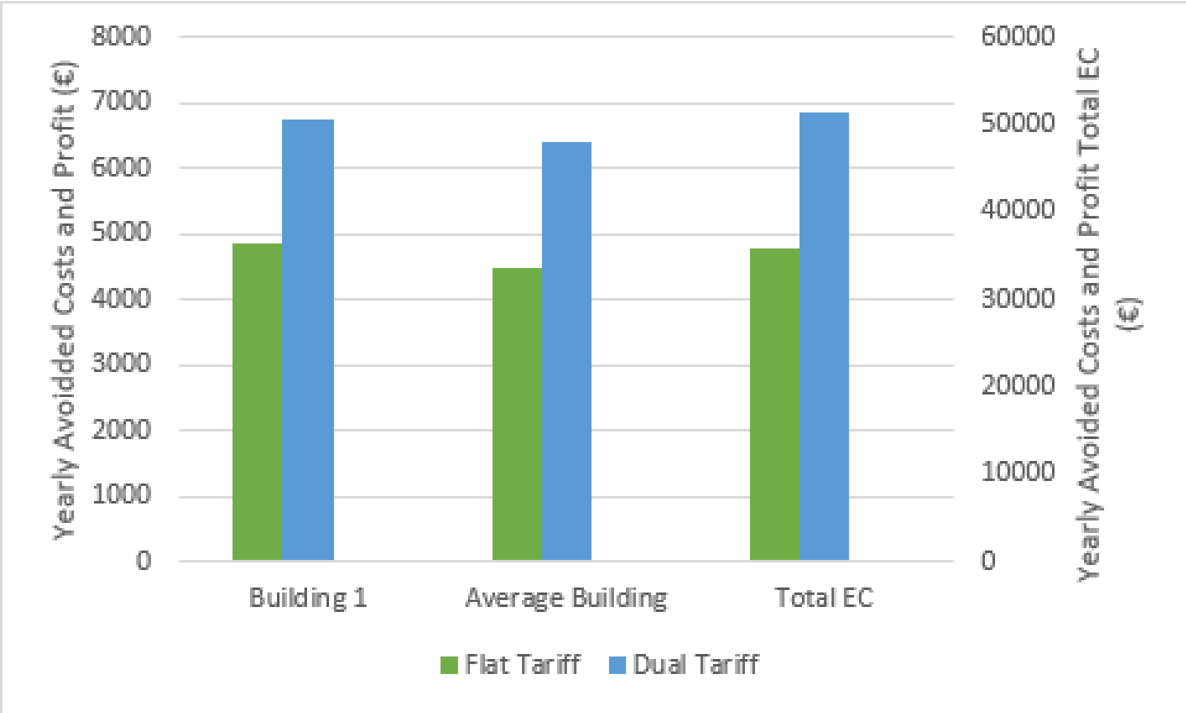

Figure C.4: Savings of having an EC