UNIVERSITA' POLITECNICA DELLE MARCHE

FACOLTA' DI **INGEGNERIA**

Corso di Laurea magistrale in **Ingegneria Meccanica**

Pianificazione di un sistema energetico autonomo per il quartiere di Vale Santo Antonio a Lisbona

Autonomous energy system planning for the Vale Santo Antonio district in Lisbon

Relatore: Chiar.mo	Tesi di Laurea di:
Prof. **Gabriele Comodi**	**Lorenzo Savini**

Correlatore: Chiar.mo

Prof. **Carlos Augusto Santos Silva**

A.A. **2019 / 2020**

ACKNOWLEDGEMENTS

I would like to express my deep gratitude to Prof. Carlos Augusto Silva, who was always very motivating and available, and helpful for any trouble. Furthermore, I am grateful for the support of Prof Gabriele Comodi who allowed me to carry out this work as a thesis topic.

Afterward, I have to thank many other people. Especially, my mother Cristina, my father Piero, my sister Giulia, my brother Giovanni, my uncle Marco, my aunt Sabrina, my Grandmother Eva, Stefano, and all the family which has always supported me whatever I did, wherever I was. I can’t find the words to express how much I am grateful to have them as family. I thank them for being my power.

Moreover, I thank my flatmates and second family Arianna and Maria. When I started the thesis, they supported me and made me feel good, despite the situation out there it was not the best.

I’m grateful to my friends from Lisbon, Giorgia, Andrea, Kuba, Francesco, Tony, Houda, Ina, Aurelien, Julien, Lars, Luca, Rico, Daniel and all the amazing people that I met along with my Erasmus. Without them, I could not have written this thesis.

I’m thankful to my friends from Ancona, among which Maksim, Federico, Antonello, Andrea, great guys with whom I really enjoyed the last years of study.

I thank my classmates and fellow adventurers, Gabriele, Stefano, Francesco, and Alessio, have been my inspiration.

And at last but not least, I’m thankful to my old friends from Montesilvano, Antongiulio, Luigi, Filippo, Mattia, Alessandro, Pierfrancesco, and the rest of the group.

ABSTRACT

The objective of this thesis is to propose an energy system that, guaranteeing thermal comfort, allows the area of Vale de Santo António in Lisbon to be self-sufficient from an energy point of view. As a starting point, it is necessary to forecast the consumption of buildings in 2050, based on the analysis of scenarios for the future evolution of energy systems and their impact on buildings in Portugal. Then, an urban energy modeling tool (UBEM), the City Energy Analyst (CEA), is used to make the consumption model of the area under analysis and create consumption scenarios. After, taking into account the expected evolution of energy systems towards decarbonization, different measures of energy efficiency and energy generation are tested to verify the potential for self-sufficiency. The results are based on the analysis and comparison of the different output elements obtainable by CEA, such as thermal comfort, final use energy consumption, equivalent kg CO2 emissions and an overall cost assessment. Observing the modeled future scenario, the results obtained show improvements in all the implemented solutions, if compared with the simulation of the current scenario of Vale Santo Antonio. In particular, the demand for energy decreases sharply, with cuts of up to 70% on the final consumption of the neighborhood, satisfying the self-sufficiency objectives for 2050 on residential. At the same time, in the most optimistic scenario, emissions are reduced by 40%, however a result that is not as satisfactory as consumption. On the other hand, thanks to the renovation, thermal comfort is guaranteed to all buildings in the winter season, one of the most serious problems to face for the neighborhood and Portugal. Thus, CEA is a modeling tool that, despite requiring a high, and often inaccessible, amount of data, could provide useful preliminary support for the energy planning of the district.

Keywords: UBEM, self-sufficiency, renewable energy systems, City Energy Analyst, energy efficiency.

SOMMARIO

L'obiettivo di questa tesi è quello di proporre un sistema energetico che, garantendo comfort termico, consenta all'area di Vale de Santo António di Lisbona di essere autosufficiente dal punto di vista energetico. Come punto di partenza, è necessario prevedere il consumo degli edifici nel 2050, sulla base dei futuri scenari del sistema energetico e del loro impatto sugli edifici in Portogallo. Quindi, uno strumento di modellazione energetica urbana (UBEM), City Energy Analyst (CEA), viene utilizzato per realizzare il modello di consumo dell'area in analisi e creare scenari di consumo. Successivamente, tenendo conto della prevista evoluzione dei sistemi energetici verso la decarbonizzazione, vengono testate diverse misure di efficienza energetica e generazione di energia per verificare il potenziale di autosufficienza. I risultati si basano sull'analisi e sul confronto fra i diversi elementi di output ottenibili da CEA, quali il comfort termico, il consumo energetico finale, le emissioni di kg equivalenti di CO_2 e una valutazione complessiva dei costi. Osservando lo scenario futuro modellato, i risultati ottenuti mostrano miglioramenti in tutte le soluzioni implementate, se confrontate con la simulazione dello scenario attuale di Vale Santo Antonio. In particolare, la domanda di energia diminuisce nettamente, con tagli fino al 70% sul consumo del quartiere, soddisfacendo gli obbiettivi di autosufficienza per il 2050 sul residenziale. Contemporaneamente, nello scenario più ottimistico, le emissioni vengono ridotte del 40%, un risultato tuttavia numericamente non soddisfacente quanto i consumi. D’altra parte, grazie al rinnovamento, viene garantito a tutti gli edifici il comfort termico nella stagione invernale, uno dei problemi più seri da fronteggiare per il quartiere e il Portogallo. Il CEA evidenzia così una modellizzazione che, nonostante richieda un’alta, e spesso inaccessibile, quantità di dati, potrebbe fornire un utile supporto preliminare alla pianificazione energetica del quartiere.

Parole-chiave: UBEM, autosufficienza, sistemi energetici rinnovabili, City Energy Analyst, efficienza energetica.

Table of contents

LIST OF TABLES

LIST OF FIGURES

1 Introduction

1.1 Motivation

Nowadays we have a lot of devices and services using energy and we take that energy for granted, forgetting that the situation will be different in some years. The global population, currently about 7.8 billion, is exponentially growing. Worldwide energy supply is still based on fossil fuels such as coal, natural gas and finally oil, major actor among the greenhouse gas producers, which will bring disastrous consequences on our planet without an immediate brake.

Renewable energy supply represents the only alternative for avoiding catastrophic climate change. Their use has increased significantly, although it still represents a small fraction of the total consumption; only 18,6 % of the total primary energy produced has a renewable source [1].

Since the beginning of the century, Portugal is contributing to the energy transition. Presently the country generates about 50% to 60% of electricity from renewable sources. However, there is the awareness that only green sources spread will not satisfy the massive future global energy demand. In fact, the demand is not fixed, but rather it will tend to increase, leaving out other problems such as the intermittency of these sources.[2].

So, how are we going to create that energy? The best answer would be “not using it”. That is what the Net Zero Emission target points to do, realizing structures that do not need to be fed by energy, so producing emissions. Most of the energy that we use seems to be indispensable, in order to feed a lot of devices that are often essential to ensure an adequate quality of life. Nevertheless, a smart transition would not aim at giving up these comforts, on the contrary it must be able to offer them while maintaining the lowest possible consumption; in other words, increase energy efficiency

Portugal in particular needs to improve in this regard. Still in 2020, thermal comfort is not guaranteed in most of the buildings, despite the average high temperatures of the country area. Enormous potential remains untapped due to the widespread use of less-efficient technologies, a lack of effective policies and insufficient investment in sustainable buildings [3]. Improving the buildings efficiency, will be possible to fix the comfort lack, without increasing consumptions.

Construction or retrofitting of Net-Zero Energy buildings must be a fundamental step for a long-term strategy that aims at energy self-sufficiency. This will require considerable engineering and customization efforts for each installation. The path to achieving this goal still has many obstacles, but not only technological and economic limitations. For instance, radically transforming the entire neighborhood will not be feasible in the center of Lisbon, or in the center of Óbidos, where many typical historic buildings are located. A neighborhood like Vale Santo Antonio fully embodies the average characteristics of buildings in Portugal, which do not need to maintain a historical form since they are relatively recent, less characteristics, in economic growth, and made up of too many obsolete buildings that require to be replaced or refurbished. Therefore, the district under consideration may represent an, hopefully valid, example for all the Portuguese districts candidate for giving the "green push" and being the embody of the future scenario.

Despite it is not a fast and simple step, many state-of-the-art tools are capable to help in this effort. In the future, the only possibility for a clean and much more populous planet is a society based on the net-zero energy. Through a correct approach to these technologies, it can be possible.

1.2 Objectives

Around the neighborhood *Vale de Santo Antonio*, located in Lisbon's municipality, a new district will be developed. This work aims to understand if it is possible to contribute to this effort by using a tool to simulate the energy system - an urban building energy modeling (UBEM), in order to define the best solutions. The study starts from a current energy scenario, which needs to be analyzed, uploaded on the software, and optimized, to propose a self-sufficient district.

The result is a proposal of the future scenario, which aims to improve strongly the thermal comfort keeping as low as possible the consumption, as well as the GHG emission. The challenge to face is to build a system capable to guarantee thermal comfort, cutting the emissions and fossil fuel dependency, achieving self-sufficiency. In order to test if the target is feasible, this thesis compares the forecast of energy consumptions with the energy demand of the optimized district (calculated by the UBEM), after providing the modeling of several solutions.

1.3 Contributions

In order to achieve the objective, this thesis uses the Urban building energy modelling (UBEM) software called City Energy Analyst (CEA). The novelty of the thesis consists in using this tool to define the retrofit strategies and energy generation solutions for the district in order to make it self-sustainable. It includes direct comparisons between similarly suitable tools, under several points of view (input, output, stakeholders, strong points, weakness, applications). Moreover, the work provides various researches about the most appropriate architectural and plant engineering approach for retrofitting in Lisbon, following the self-sufficiency path.

1.4 Structure of the thesis

The thesis is structured in six main chapters.

The Chapter 1 included the motivational context, objectives and contributions.

The Chapter 2 introduces the World, European and Portugal energy’s panorama.

In Chapter 3, literature review regarding the modeling of buildings energy through the latest tools, to provide proper knowledge and context for the analysis. First, it introduces UBEMs and their features. Secondly, it provides some examples of UBEMs and their application.

In Chapter 4, the current scenario of the case study is described, but also how the tool must be set up to provide a real and trusted representation of the district.

In Chapter 5, the solutions for a self-efficient district are presented.

In Chapter 6, a final discussion collects the benefits and the drawbacks of the solutions

Finally, Chapter 7^h summarizes the conclusions of the work.

2 The energy trends

2.1 World and European overview

Around 55% of the world's population lives in urban areas, a proportion that is expected to increase to 68% by 2050. Occupying less than 2 percent of the Earth's land, the cities account for 60-80% of global energy consumption and 75% of carbon emissions.

All these data confirm the need to set the construction of sustainable cities as a goal. The Agenda 2030, with the *Sustainable cities and communities* goal, following the Paris Agreement statements, provides motivation and guidelines to achieve this ambition.[4] As stated, the main targets of a clean city are "to be able to feed itself with a sustainable reliance on the surrounding natural environment and have the ability to power itself with renewable sources of energy"; in other words, to create the smallest conceivable ecological footprint while also producing the lowest quantity of pollution achievable. All of this has to be accomplished by efficiently using the land in ways such as composting used materials, recycling, and/or converting waste-to-energy.

However, we must understand which are the elements of the city that weigh the most and which should be given priority. First, the matter of the building, which includes the residential and service sectors. Buildings have the highest consumption compared to the other consumption sectors and only the household appliances energy use is nearly 15% of global final electricity demand [3]. From a UN report about investing in energy and resource efficiency of the cities, "tackling the energy demand of existing building stock is a priority for cities"[5]. In addition, the EU Commission agreed by saying that energy efficiency will play a central role in decarbonizing industrial processes but much of the reduced energy demand will occur in buildings, in both the residential and services sectors, which today are responsible for 40% of energy consumption [6].

2.2 Case study

2.2.1 A district of Lisbon

The thesis case study is in the capital of Portugal, Lisbon, with a population now estimated at 2,956,879 with a growth rate of 0.50% according to UN World Urbanization Prospects. These estimates represent the urban agglomeration of Lisbon, which typically includes Lisbon's population in addition to adjacent suburban areas, while the actual Municipality, which includes the historical center, counts with 505,526 inhabitants. Although the Growth Rate (%) is a bit decreasing, the forecast shows that in 15 years the Metropolitan Area will still count around 3,124,833 inhabitants [7][8].

Lisbon is one of the largest urban areas in the EU and continues to grow with each passing year. The city is home to the administration of Portugal and is, therefore, a hub for both city residents and international guests. About 26.7% of people (3,000,000) of Portugal live in the Lisbon metropolitan area, 19.4% (550,000) of which live in the city of Lisbon. As the whole country, the city stands out for the average age of the inhabitants pretty high: senior people (65 years old) will be 27.4 % of the Lisbon population by 2030 [7].

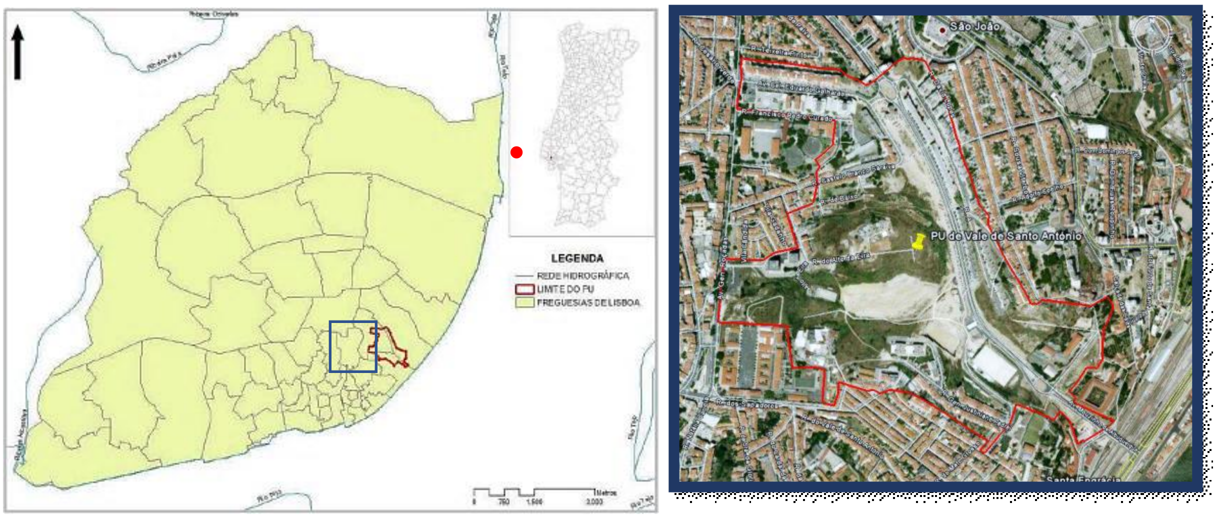


Figure 1. Localization of the Vale Santo Antonio district in the municipality of Lisbon, Portugal [9]

Vale Sant Antonio (VSA) is a district of the old part of Lisbon municipality. It includes an area of 51,551 m^2 mostly made of multi-residential buildings. A huge percentage of the area, 29%, will be urbanized with new buildings in a few years, while the existing constructions are basically old types prior to the 70s (figure 1) [10].

2.2.2 Thermal comfort

Lisbon is one of the warmest capital cities in Europe, one of the best climates in the world rankings. It has a Subtropical-Mediterranean climate, which means that in winter temperatures are mild and in summer hot, but not too much. The wind from the Atlantic Ocean brings quite a lot of rain but keeps the temperatures moderate. Moreover, the Lisbon region is the wealthiest in Portugal, and it is well above the European Union's GDP per capita average (it produces 45% of the Portuguese GDP) and in the last twenty years the technologic developing grew up significantly. [11]

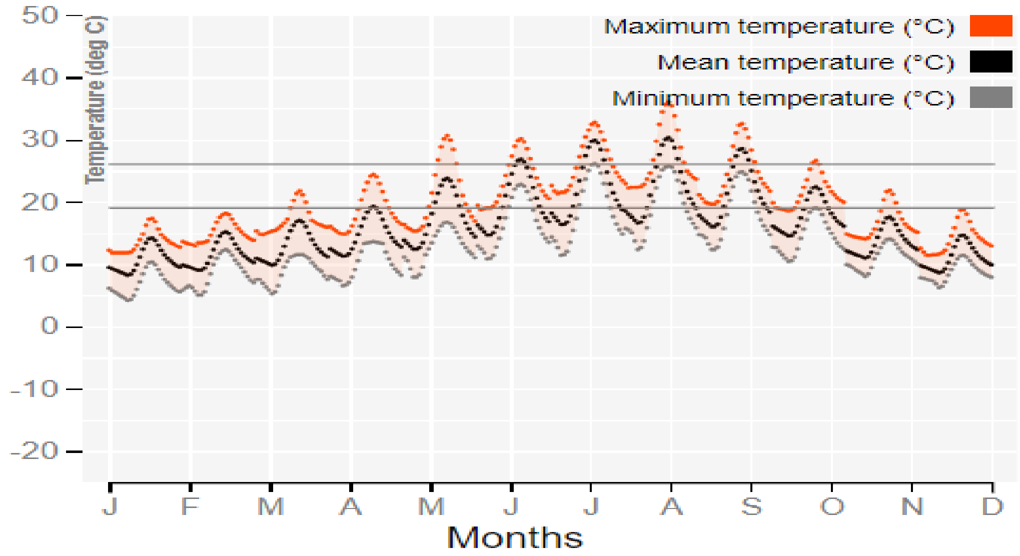


Figure 2. Lisbon outdoor temperature with upper and lower thermal comfort bound (Climaplusbeta) [12]

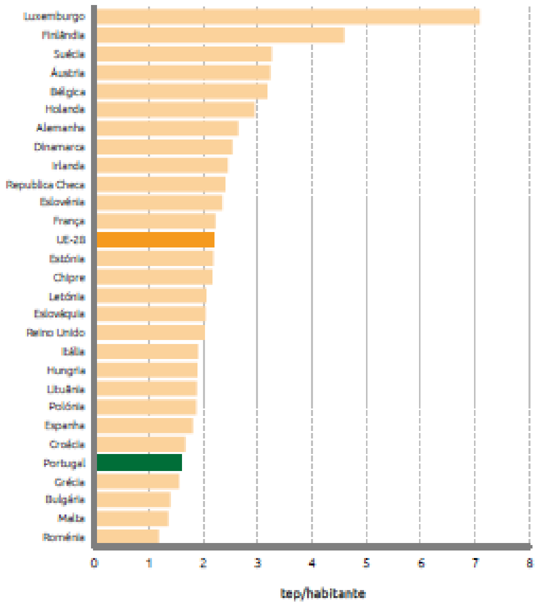
However, for many years after of the XX century Portugal maintained a lower standard of living than the rest of western Europe, due to an economy which has grown, but not as much as the rest of the Continent. Even though winter is quite short, thermal comfort in this season has always remained as a serious problem. A standard methodology has been used to compare cold-related mortality rates in different countries, according to a study by the University of Dublin. What they found out is that Portugal is the second worst country among a list of thirty Europe countries, preceded only by Malta. This has long been known as the 'excess winter mortality paradox' in which people are more likely to die during cold spells if they live in more southerly areas of Europe. Many factors appear to contribute to this effect. Spending proportionally more of income on heating costs is an obvious protective factor, which in the coldest winter regions is virtually non-negotiable for survival. Other protective factors include housing quality (especially insulation and energy efficiency of building fabric), lifestyle adjustments to cold such as wearing adequate protective clothing and altering activity patterns when temperatures are low [13].

Nevertheless, by 2050 in Portugal, an increase in residential thermal comfort is expected, both in heating and cooling (thermal comfort will triple in heating and double in cooling compared to the current situation). This increase in comfort comes from the electrification trend, the use of more efficient equipment (e.g. heat pumps), the increased use of insulation materials and higher rates of urban rehabilitation (e.g. replacement of windows). Insulation measures are estimated to reduce heating energy consumption by 26% by 2040 and around 50% by 2050 in the residential sector, so this increase in comfort does not result in a direct increase in final energy consumption[14].

2.2.3 Energy scenario

Comparing the consumption of energy per capita in Portugal with the countries of the EU-28, it was found that in 2017, Portugal was the 6th country with the lowest consumption of primary energy per inhabitant (-27.6% compared to the average EU-28), while in terms of final energy consumption per capita, Portugal was the 5th country with the lowest consumption per inhabitant (-26.8% compared to the EU-28 average, Fig. 5).

These numbers could be defined positively in a “green view” but are also explicatory of the thermal comfort issue.



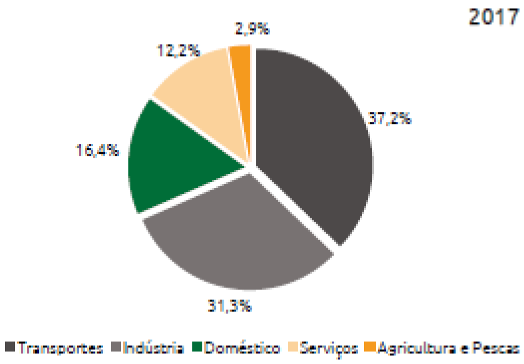


Figure 3. Portugal’s consumption per sector (right)[15].

Figure 4. Consumption per inhabitant in Europe (Left) [15].

Consumption in the domestic or residential sector shows a serial drop in 2010, probably caused by the world crisis and the consequent economic crisis in Europe and in particular in southern countries (Greece, Portugal, Spain and Italy). From 2010 to 2017, consumption in the residential sector decreased by 13%, with a decrease in the consumption of petroleum products, mainly heating diesel and GPL, in which the consumption fell by 38%. In the same period, the consumption of natural gas decreased by 16%. Gas remains an option in housing in the time horizon until 2040, but it expected to virtually disappear over the following decade. The Firewood (biomass) emerges as the second main energy source consumed in Portuguese housing in 2010, with a weight of 24.2% of the total consumption. Biomass usage options follows the same trend of the natural gas, although their importance is different in urban and rural areas (more decentralized).

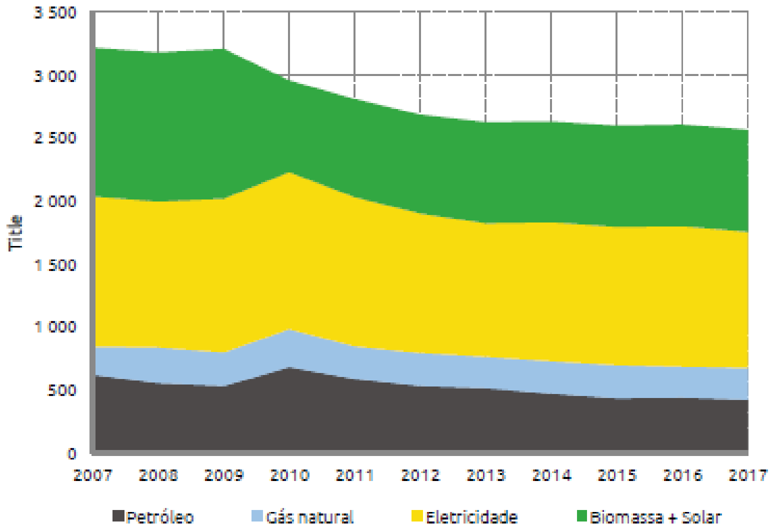


Figure 5. Energy demand in residential over the years [ktoe][15].

Electricity, although decreased by 13% from 2007, still emerges as the main source of energy consumed in the domestic sector in Portugal, representing 44.1% of total energy consumption. This energy vector is the one that underwent the greatest change and is expected to increase the next years. Some estimations say that it will reach around 83% in 2050. This growth in electricity consumption will be directly linked to the increased thermal comfort and the growth in the number of electrical equipment available in homes.

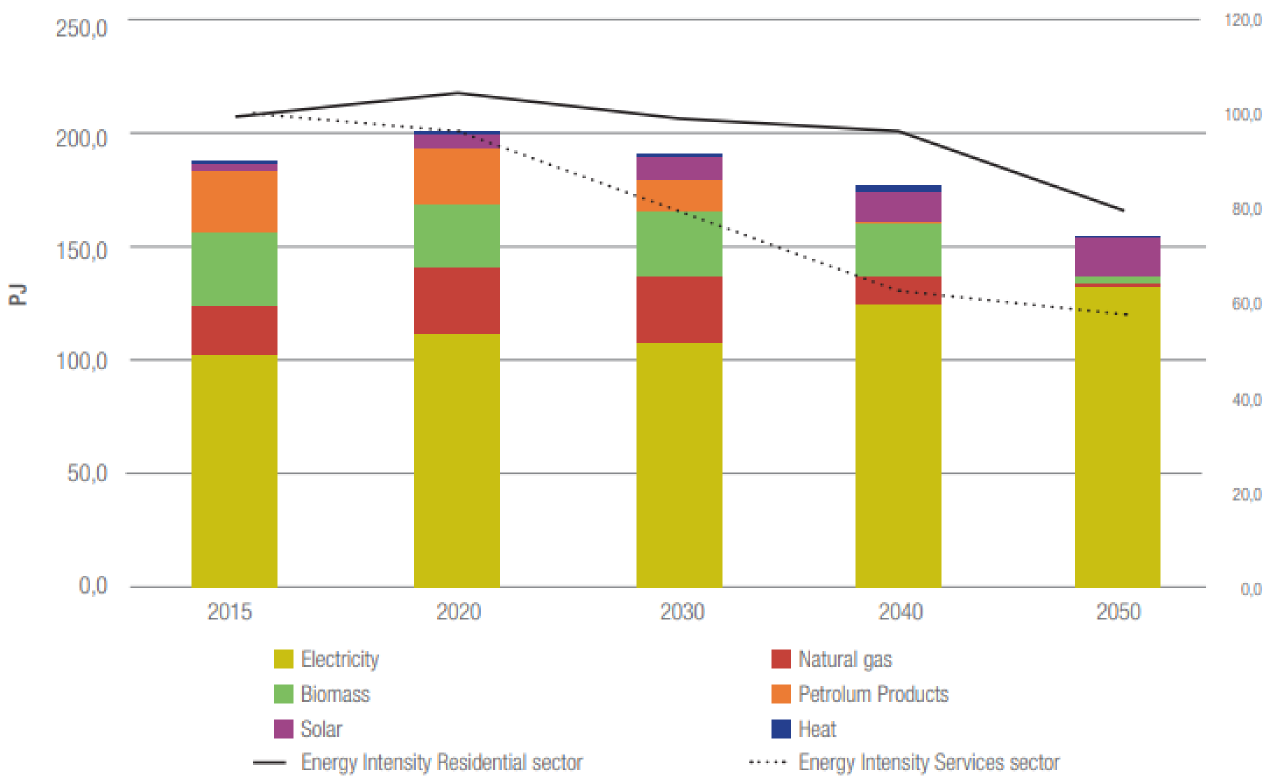


Figure 6. Evolution of final energy consumption [PJ] and energy intensity in buildings (residential and services) [14]

Energy consumption from renewable sources, such as biomass and solar thermal, grew by 11% in the same period [15] (ICESD) , but it is set to rise. The percentage of incorporation of renewable energies in heating and cooling, according to the long-term strategy for carbon neutrality of the Portuguese economy by 2050, should go from 35 to 70% (heating and cooling respectively 66% and 68%) [14] [16].[17]

FINAL ENERGY CONSUMPTION	2015	2020	2030	2040	2050
	188.46	**201.64**	**194.55 I 192.97**	**176.67 I 177.64**	**156.57 I 156.34**
Electricity	104.62	112.55	109.58 I 109.52	124.83 I 125.56	134.69 I 132.99
Natural Gas	20.45	29.24	30.65 I 29.87	13.97 I 13.28	1.33 I 1.31
Biomass	33.27	28.79	28.02 I 28.29	21.76 I 23	1.7 I 4.03
Petroleum Products	25.60	24.29	15.23 I 14.27	1.08 I 1.01	0.00
Solar	3.36	5.33	9.46	13.63 I 13.53	18.51 I 17.71
Heat	1.16	1.44	1.61 I 1.56	1.39 I 1.26	0.34 I 0.3
Unit: PJ					
ENERGY INTENSITY					
Residential	100.00	105.36	108.69 I 101.34	105.88 I 96.76	93.29 I 80.05
Services	100.00	96.19	83.1 I 80.74	66.46 I 64.66	57.74 I 56.72
Unit: (2015=100)					

Figure 7. Consumptions in residential and service by type of source [PJ] (Portuguese ministry of Environment and Energy Transition, 2019) [14].

2.2.4 Emissions

Buildings are currently responsible for 5% of national GHG emissions. They are major energy consumers, currently accounting for about 30% of final energy consumption, so one of the most important sources of CO2 emissions. In buildings, energy is consumed for the provision of energy services such as space heating and cooling, lighting, refrigeration and cooking, sanitary water heating, among others. Despite the expected increase in demand for cooling services, due to rising average temperatures, and for other electrical uses associated with servers, clouds, etc., these sectors still show high potential for reducing emissions, which will already start to be felt over the next two decades. [14]

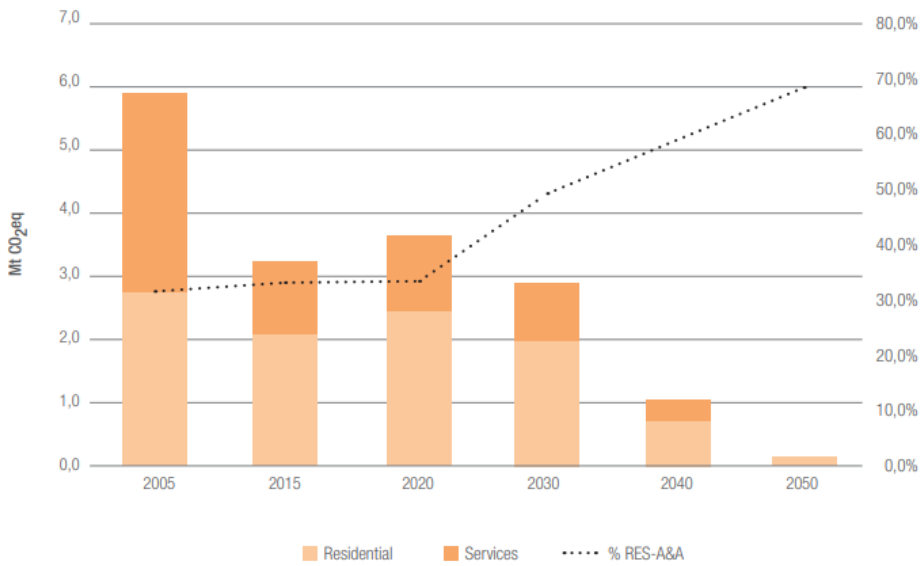


Figure 8. Evolution of emissions from the residential and services sectors and percentage of incorporation of renewable energies in heating and cooling [14]

Thus, emissions reductions are estimated for 2050 in the residential sector to be at -97% and -96% and 100% in the services sector (compared to 2005). Concluding, the expectations for 2050 involve a possibility of a decrease in energy consumption per m^2 in residential buildings from -7% to -20% compared to today, also thanks to the adoption of high-performance electrical equipment such as LEDs for lighting and equipment of higher energetic efficiency classes. [14]

2.2.5 Main preliminary considerations by type of use

Taking into account the different energy uses in the housings, it is verified that it is in the kitchen that occurs the majority of global consumption, corresponding to more than 1/3 (37%), followed by water heating with 31%. However, the dominant energy source is different depending on the type of use, as in the Kitchen dominates the electricity, while in water heating is predominantly used the GPL bottle.

Considering the type of final use of electricity, it is verified that electricity consumption in the Kitchen and Electrical Equipment was the highest, with 40% and 33% of the total consumption in 2010.

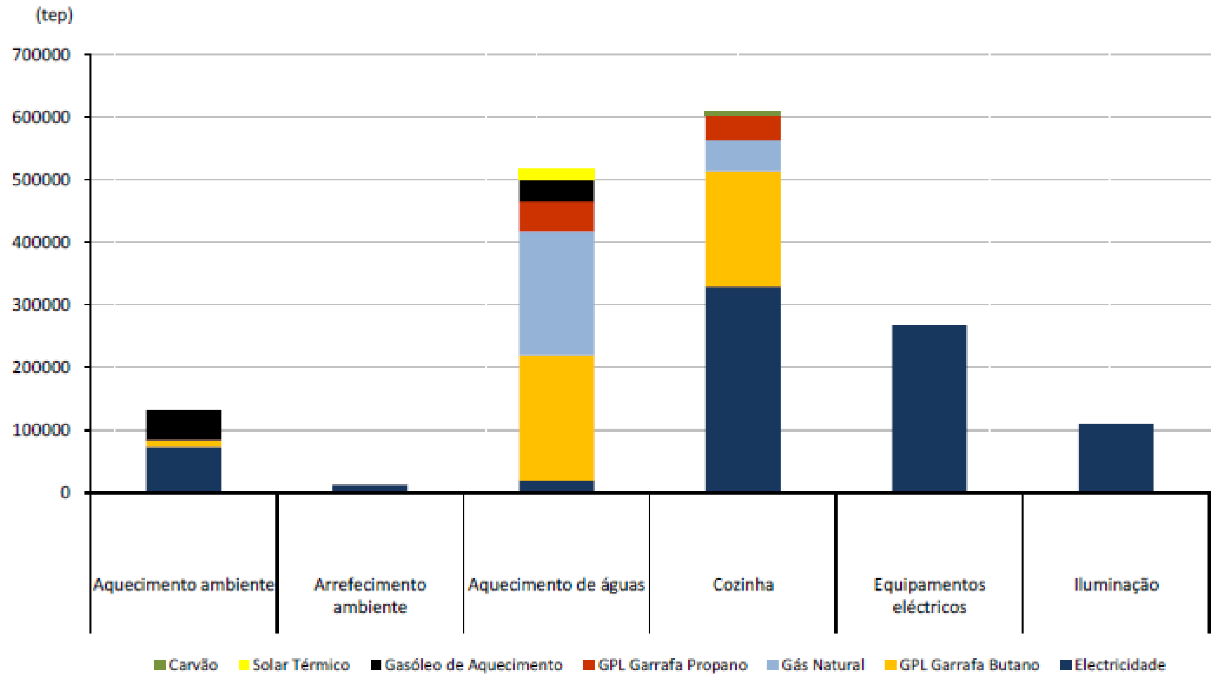


Figure 9. Energy consumption [toe] distribution in residential buildings by type of use and source (INE, 2010)[18].

It is also noteworthy the energy consumption for the heating of the environment, which corresponds to 8% of the total consumption of energy in 2010. Electricity was the main source of energy used in the heating of the environment. The heating diesel still represents an important share of energy consumption in this type of Use. In terms of final use, the heating diesel consumed is intended for heating the environment and Water heating in remote locations, where gas supply is difficult. Coal consumption, although reduced compared to other energy sources, was mostly used in the Kitchen (corresponding to more than 95% of its use), and it should be noted that more than 90% of the coal consumed in 2010 "charcoal", thus contributing to the consumption of renewable energy sources in the domestic sector.

In terms of renewable energies, it is highlighted the use of solar thermal energy in housing, essentially for water heating. Overall, the consumption of renewable energy sources in the domestic sector, accounted for about 25% of total energy consumption in housing in 2010, with contribution of wood the most relevant factor (in 2020 this percentage is even higher) [18].

2.2.6 Autonomous systems

Autonomous system is defined as a complex of autonomous buildings, or better known as Zero-energy buildings. According to EU *nearly zero-energy building* means a building that has a very high energy performance. The nearly zero or very low amount of energy required should be covered to a very significant extent by energy from renewable sources, including energy from renewable sources produced on-site or nearby. Basically, for be self-efficiency a building needs to: achieve thermal comfort entirely passively, offset all annual electricity with renewables and eliminate domestic water heating energy. The house insulation and green powering play a key role, such as solar heating and heat pumps.

In Europe there is a large variety of concepts and examples for nearly zero-energy buildings. There are non-governmental examples putting emphasis on different aspects (like the *ZeroHaus* or *Passivhaus*, Passive House in English) as well as government-initiated programs which usually focus on the buildings' efficiency (e.g. Minergie from Switzerland). In most cases the heating demand is drastically reduced by following the Passive House concept; in some cases, electricity use by lighting and appliances is included. On-site power generation from renewables, usually from PV, balances demands of heat pumps, other HVAC systems and use-specific consumers. In multi-fuel buildings the on-site power generation additionally balances the fuel or district heat use on a primary energy or CO2 emission basis. In some commercial buildings or large domestic renovation projects the balance boundary is expanded to off-site renewable energy generation as on-site options are found to be insufficient.

It is noticeable that mid-European building practice gives highest priority to efficiency measures. On the other hand, in south-European countries as Portugal, there are even more opportunities to exploit. PV and Solar thermal have great potential due to high radiation levels and short payback times. Solar thermal is most suitable for less sophisticated Solar Domestic Hot Water preparation (SDHW); and high efficiency compact low-cost thermal storage systems. Both systems are still a growing market. Moreover, reversible systems like heat pumps are economically attractive in the south climate. Combi-systems have the biggest potential for market growth. Especially, the medium size still growing market [19]

Therefore, thanks to these advantages, a Portuguese district as VSA, has the huge opportunity to reach the NZEB goal, without scarifying so much energy and capital expenses. Both building from scratch and renovating, a high insulation envelope, thermal comfort could be guaranteed for most of the year, almost breaking down to zero the bills. The several resources belonging to the climate allow keeping very low the energy consumption, if the system, generation, and emission plants, is supported by an adequate level of efficiency. The years of experience gained by the association involved, like Passivhaus, allow ensuring an actual working project, which has been already tested and approved. Reliable online platforms as well as Passivhaus are available to offer architecture and energy system standard features in order to reach this goal.

Figure 10. Freiburg autonomous district [20]**.**

3 Literature review

Urban modelling is a vast subject that can be addressed at different levels of detail, its nature is inherently dynamic since it concerns flows of goods, energy, waste and people. The possible analyses are numerous, and include buildings, traffic, renewable energy sources (RES), energy network, etc. However, in the field of urban modelling, it is possible to identify one main area, the UBEM, focused on buildings modelling at urban scale [21].

3.1 Urban building energy modelling (UBEMS)

Urban building energy modeling refers to the computational modeling and simulation of the performance of a group of buildings in the urban context. This category shows great heterogeneity and includes different types of tools and methodologies with different scopes. In general, the goal is to provide quantitative insights (e.g., annual or seasonal energy use and demand, potential of renewable power generation) to inform urban building design and operation, as well as energy policymaking. Urban building performance metrics include near-term operational efficiency (e.g., energy use and demand at the daily, monthly, and yearly time frames), short-term demand response (e.g., electric load shedding and shifting at the minute to hour time frame), long-term sustainability (e.g., GHG emissions, impacts of climate change on energy demand at the year to decade time frame), and event-driven resilience (e.g., impact of extreme weather events such as heatwaves and wildfire on energy use, power supply, and occupant health at the day time frame). UBEM can also estimate the potential of renewable power generation from photovoltaics (PV) or wind turbine systems located on rooftops or integrated into building facades. For electric vehicle (EV) charging that uses the building power system, UBEM can integrate the EV loads into the building's overall energy demand [21][22].

3.1.1 Modelling approach

UBEM can use different modelling approaches: top-down and bottom-up.

Top-down. The current urban energy flow modelling is mostly based on top-down building stock energy models, estimating the energy consumption of buildings from agglomerated data on large scales. Namely, top-down models start with the building energy demand for one region and successively they subdivide the whole stock into smaller subsections, providing estimates of the energy analysis if more buildings of a certain type were to be built. The approach is usually data-driven, with statistical and regression models integrating building stock data, technology adoption models, and economical models to provide high-level building energy policy evaluation and scenario analysis, as well as a technology R&D roadmap. These models need few input data to describe buildings that usually consist of easily available aggregated data. However, this determines a limitation too. Such models are limited in their predictive ability when investigating the performance of a group of buildings in an urban context, since they try to predict the future energy consumption on past interconnections between the energy and the economic sectors. A second drawback is the lack of technical detail [21][22].

Bottom-up. On the other hand, bottom-up urban building energy models are expected to achieve the goals of investigating/planning the integrated energy supply-demand scenarios. Bottom-up models are based on physical descriptions and engineering calculations in and around buildings, which are used to analyze the operational energy costs and dynamic performance for the group of buildings at high spatial and temporal resolutions. Bottom-up models calculate the energy consumption at a single building scale and then aggregate the results at different levels, considering an integrated framework. To perform properly, they need a large quantity of data whose availability may be hindered by privacy and other issues. This category is the one that this thesis intends to study with major detail, since it includes the tools that may better evaluate scenarios for current and future urban environments management and design. In the next sub-chapter (3.2) will be introduced a selection of the more interesting bottom-up tools.

They mainly use different strategies to create clusters of similar buildings (called archetypes) to assign characteristics to the 3D representation of the building stock that is usually based on Geographic Information System (GIS). The two main parameters used to create archetypes in the building stock are the layout of the buildings (geometry and typology) and their year of construction. In other cases, specific technical features of the building regarding the envelope or the systems, or the occupancy profiles are used. They are all characterized by different but simplified Graphical User Interfaces (GUIs). Among this typology of models, further differentiation is identified: physics-based, reduced-order and data-driven models [21][22].

3.1.2 Types of models

Physics-based models. The earliest physics-based UBEM models implement tools directly from Building Energy Modeling (BEM), and they perform co-simulation with other detailed software for specific topics. They are usually based on simulation engines used for BEM, but they optimized the processes to be scalable for large building stocks.

The EnergyPlus simulation is one of the engines, which provides capabilities for in-depth analysis of complex building systems. It is a thermal modelling software supported by the US Department of Energy and one is widely used for the design and certification of energy-efficient buildings. EnergyPlus prototype building energy models enable wide adoption of EnergyPlus for urban building stock energy research. Often, they use OpenStudio Software Development Kit (SDK) to generate energy models for EnergyPlus simulations. Another dynamic simulation engine, IDA ICE, is used to replicate the energy consumption of district buildings. Physics-based modeling approaches capturing the full dynamic of building performance offer the highest resolution. At large-scale, the characterization of buildings is not easy and manually feasible, as for single buildings. However, in the last years, these models experienced a rapid evolution: numerous researches deal with this problem and they propose methodologies to simplify the model enough to reach reasonable time and computing efforts [21] [22].

Reduced-order models. Reduced-order modeling approaches are used widely to provide a quick evaluation of urban building energy performance, requiring simple inputs aligned with normatively structured model parameter values. There are different forms of reduced-order models. Calculation standards developed by the European Committee for Standardization (CEN) and the International Organization for Standardization (ISO) define the calculation method using a set of normative statements containing the physical building parameters and building systems for different building types. Traditionally these normative calculation methods have been used for energy performance rating in European countries. The reduced-order models have modeling accuracy drawbacks, yet advantages such as computational efficiency and fewer inputs requirement. It is, however, the typology of tool chosen for this thesis work [21].

Data-driven models. Data-driven modeling methods are applied to urban building energy prediction, which relies on real measured data, and pre-defined databases for building type, age, and locational data. Regression methods are used to derive inverse statistical models, which infer building design or operational parameter inputs from known outputs such as energy consumption data, locational datasets, and public records [21].

3.1.3 Input Data for models

An important factor to consider include the availability and quality of input data. Data is crucial in urban scale energy modeling, and it usually comes from diverse sources. Thus, integrating and processing data into a standardized data format is critical for effective interoperability among urban energy modeling applications. All the tools require as input data: the description of the geometry under analysis, the thermo-physical characterization of the buildings, and the weather dataset.

Geometry. The basic method to set the geometry of the building stock is by uploading a manually created 3D model. Since, on a large-scale, it can be difficult to create a detailed 3D model of the built environment, many tools are directly integrated with a Geographical Information System (GIS) tool. The primary data formats to support UBEM include Shapefile/FileGDB, GeoJSON, and CityGML. The ESRI Shapefile and FileGDB formats [23] are popular geospatial vector data formats used by GIS software tools. They typically include two-dimensional (2D) GIS-based building footprint information and a table of building properties or attributes. Geo-JSON is a data format based on JSON (JavaScript Object Notation) for encoding a variety of 2D GIS data structures, which is friendly to web applications built upon JavaScript. However, the Shapefile/FileGDB and GeoJSON formats do not provide a schema to define the building properties, leading to inconsistency among different datasets. On the other hand, CityGML is an international Open Geospatial Consortium (OGC) standard that provides an open data model to represent and exchange digital three-dimensional (3D) models of cities and landscapes. Many UBEM projects selected CityGML as the data model to represent and exchange 3D city models, especially for European research projects. The CityGML Energy ADE extends the CityGML standard by features and properties, which are necessary to perform an energy simulation and to store the corresponding results. It helps running an urban scale simulation, since it includes further details of the buildings in addition to the ones available in standard geometry CityGML files, such as the thermal zones that compose a building, the building fabric, the occupancy conditions, and the technical systems. These advanced datasets are useful to easily run simulations on a large-scale. (e.g., epw, txt, ddy, etc.). However, these geographic files are not always available for all cities and regions, especially for developing countries, and thus, these methods could be not easily applicable in all contexts. Therefore, all the tools allow the user to import a geometric model of the area of interest from manually created 3D files [21][22].

Archetypes. A fundamental phase of the settings is the characterization of the 3D geometry. Building fabric, technical systems and schedules of buildings' uses must be assigned to each 3D geometry to be treated as a building during the simulation. Some tools use a simplification method that, based on just a few input data, can assign the characteristics to the buildings via archetypes. Since archetypes need a large quantity of data, almost all the tools propose to the user already developed archetypes [21][22].

Weather. The weather file is essential for city modeling. They can include e.g. weather dry bulb temperatures, solar radiations, relative humidity, wind speeds, and directions. Dealing with cities' simulation, also the urban effect on climate (e.g. heat island effect) should be considered, thus, urban weather datasets should be created. The historical weather data in the typical meteorological year (TMY) format for building performance simulation are widely available for more than 2100 cities worldwide. Other boundary conditions are the energy conservation measures to be tested and the energy targets to be achieved [21] [15].

3.1.4 Scale

A fundamental aspect that has to be considered, when running a simulation, is the scale of the building stock that the tool can manage. With scale, it is intended the dimension of the area or the number of buildings that a tool is able to analyze. Several UBEM tools cover city-scale energy analysis, others are more prepared for a district-scale. In the next chapter will be specified how each shows a different approach. There is, nevertheless, a difference between the intrinsic limitation of the tool and the practical one.

An issue concerning the scale is about the terminology. The term “city” includes, indeed, a wide variety of scales: from Shanghai (its area is about 6300 km2) to Milan (its area is about 182 km2). The basic case is the one of a single building, this case is easily modeled with traditional BEM tools, also subdividing it into thermal zones. When multiple buildings are aggregated together and divided from other buildings by streets, they can be defined as a block. More blocks together can form a neighborhood, that can be aggregated to a district. The sum of all the districts creates a city. The six UBEM tools considered can perform simulations at the scale of the block, of the neighborhood, of the district, and of the city. However, depending on the features of the tool (e.g., typology of simulation, inputs needed, etc.) one tool could facilitate large-scale analysis respect to another. In general, there is not a specific computational requirement, and the time to run a simulation depends on the computational capacity of the CPU and of the complexity of the analysis [21][22].

3.1.5 Web-based vs. standalone desktop applications

Recent trends show that many tools leverage on web interfaces to visualize energy data for benchmarking, as well as simulation results for detailed analysis of urban buildings. Web-based tools create energy models of urban buildings in 3D laid over a map system. They effectively display buildings filtered by size, type, location, and building systems, and visualize simulation results using color-codes layered to building models to explain energy performance levels. One of the main skills of the online platform is that it runs the simulation without the limitation of a personal computer. There are also stand-alone desktop application-based tools to load data, create and run energy calculations, and visualize the results; these tools typically use a third-party graphical interface that interacts with a calculation engine or data libraries [21][22].

3.1.6 Outputs

What the UBEM tools can basically calculate is the end-use energy. For example, for almost all of the UBEM tools, domestic hot water and electricity use are direct outputs. Other possible outputs concern transport and mobility.

All the tools provide outputs in the form of data files (usually in CSV-format), allowing the easy post-processing of the results. All the tools, except TEASER, are equipped with automatic interfaces for the visualization of the results on the 3D geometry. With this type of visualization, the results are easily understandable and communicable [21][22].

3.1.7 Stakeholders

Potential users and stakeholders of UBEM include urban planners, designers, architects, engineers, energy modelers, utilities, city managers, researchers, technology vendors, governments, and policymakers. They could be interested in implementing UBEM tools for their different needs. Aligned with the stakeholders' interest, potential applications of UBEM can be summarized in three domains: end-use energy auditing and bench marketing, demand energy forecasting, and design of building retrofitting (at the urban scale) [21][22].

3.2 UBEM tools

Six different tools were selected among the physic-based, bottom-up models, since they are the most known, modern and their use showed a closer connection with the thesis work. Table 1 resume the tools main information.

Table 1. Classification of the tools analyzed

Model	Tool	Developer	Website
Physic-based model dynamic simulation method	Umi	MIT	http://urbanmodellinginterface.ning.com/
	CityBES	LBNL	https://citybes.lbl.gov/
	CitySim	EPFL	https://citysim.epfl.ch/
Reduced-order calculation method	SimStadt	Hochschule für Technik Stuttgart	http://www.simstadt.eu/de/index.jsp
	TEASER	RWTH Aachen University	https://github.com/RWTH-EBC/TEASER
	CityEnergyAnalyst	ETH Zurich	https://cityenergyanalyst.com/

3.2.1 UMI

The Urban Modeling Interface (UMI) is a Rhino-based design environment for architects and urban planners to develop an urban modeling platform. It evaluates the environmental performance of neighborhoods and cities with respect to operational and embodied energy use, walkability and daylighting potential. Focus users are urban designers and planners, municipalities, utilities, sustainability consultants and other urban stakeholders. UMI can be classified as a physics-based model tool and it uses an EnergyPlus engine [24][25].

3.2.1.1 Features

The key positive (✓) and negative features (x) are:

- ✓ Detailed. Umi offers detailed energy performance analysis built atop of the EnergyPlus engine for dynamic energy simulation of urban buildings.
- ✓ Weather input. Umi is integrated with the Urban Weather Generator tool. It exploits a variety of characteristics of the urban area to convert a weather dataset of the rural station into a usable urban weather dataset accounting for hourly urban heat island effects.
- ✓ Large scale. UMI enables an analysis of a citywide building energy performance and retrofit strategies for 92,000 buildings in Boston but is also able to run simulations evaluating the efficiency of a district considering its walkability.
- ✓ Extra analysis. The software is able to estimate extra values like the level of walkability, bikeability, daylight and lifecycle among a district.

Figure 11. Examples of UMI dashboard's elements; extra values [26].

- ✓ UMI directly performs the analysis to calculate the solar potential for the installation of PV panels.

- × It requires Rhino, a commercial tool.
- × Based on the simulation engine EnergyPlus, running very detailed analysis, has some limitation of a personal computer, contrary to web-based software (CityBES) or tools which use simplified methods (SimStadt, CEA). Moreover, in order to evaluate different scenarios with UMI, at the current release, the input data should be changed, whereas other tools don't need it. This example does not mean that UMI is a less powerful instrument, but that differences exist between the tools, although they use the same calculation engine (e.g. CityBES) [24][25].

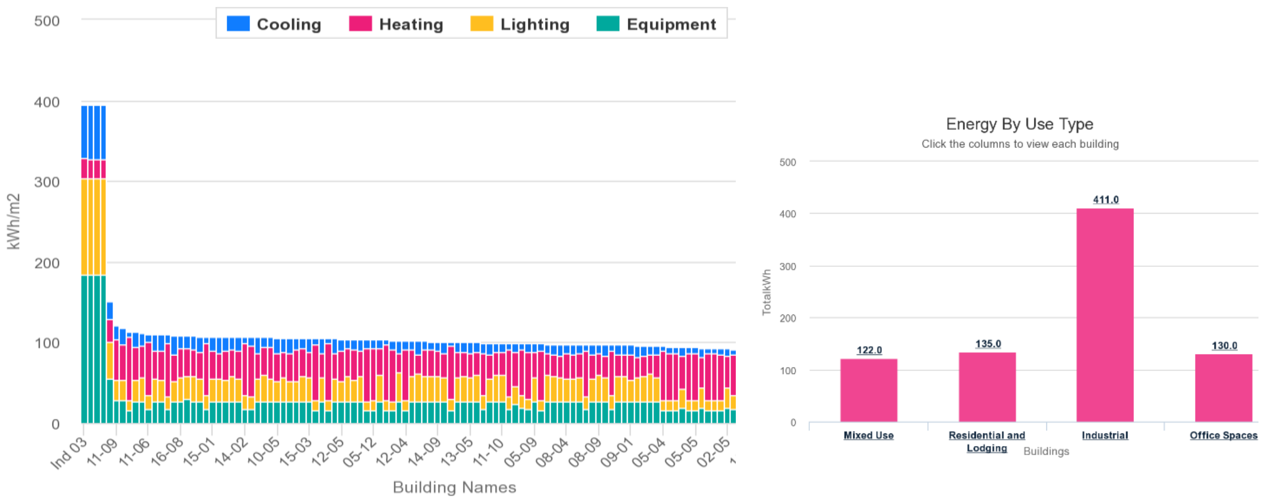


Figure 12. Examples of UMI dashboard's elements [26].

3.2.1.2 Applications

In 2011 the MIT's team started to work on Cambridge, a city part of the Boston urban area. The work on the city continued with other projects in 2013,2014,2016 and 2017. The sustainable design lab at MIT has developed a citywide building energy model for Boston, working in collaboration with the Boston Redevelopment Authority and MIT Lincoln Laboratory, with funding from the Massachusetts clean energy center. The analysis begins with the GIS database maintained by the city of Boston. GIS stands for geographic information systems a common data format that combines spatial information with a diverse range of statistical data Boston's GIS database enables users to connect multiple data types together such as building geometry parcel use and property tax assessment information. Based on these data sets, the MIT team in consultation with local building experts divide Boston's building stock into 48 building archetypes based on 12 use categories, such as residential and office and for time periods of construction. The team assigned a diverse set of properties to these archetypes including wall and roof constructions building occupancy time schedules electric lighting and thermostat settings and HVAC systems. To properly consider local weather conditions the model incorporates climate data collected over several years at Logan Airport including hourly values for air temperature and relative humidity as well as wind and solar radiation. An urban energy model also requires information about the geometry of each building. The GIS base file contains detailed building footprints that are extruded based on documented roof heights. The resulting outer building envelope is then further subdivided into volumes for each independent floor. Lastly, windows are automatically generated. The tool then incorporates the context geometry of surrounding buildings as well as local climate conditions into an energy model. The simulation results include detailed electricity and heat fuel demands in each building for every hour of the year. By repeating this process for every building in Boston the sustainable design lab creates a comprehensive hourly energy use profile for the entire city. Spatially mapping this information makes it possible to analyze when and where high energy demands occur, helping to visualize problem areas and identify key opportunities for improvement [26].

Several other projects in further cities were developed. Haiti (2011), Chicago (2011), Beijing (2011), Seville (2011), San Francisco (2013), Kuwait (2014,2016) and Kigali (Rwanda 2017) are some examples.

There were four UMI applications in Lisbon between 2016 and 2017. The whole collection of these projects aimed to build a sustainable neighborhood where once a gas power plant was in operation. Natural ventilation analysis, building-integrated agriculture, seasonal thermal storage, cardio community and reducing site EUI (energy unit intensity) are the main topic of the projects [27] [40] [28]

3.2.2 CityBES

CityBES is a web-based data and computing platform created by LBNL (Lawrence Berkeley National Laboratory). It focuses on energy modeling, benchmarking and performance visualization of a city's building stock to support district or city-scale energy efficiency programs. CityBES uses and international open data standard, CityGML, to represent and exchange 3D city models. CityBES employs CBES to simulate building energy use and calculate savings from energy retrofits. CityBES targets urban planners and developers, city energy managers, building owners, utilities, energy consultants and researchers [22], [29], [30], [31], [32], [33].

The data used by the tool consists of Cities' building datasets (GIS) and user-selected ECMs. City's GIS dataset in GeoJSON or CityGML. The Archetypes must include GIS footprint, building height, number of stories above ground, number of stories below ground, total floor area, heated floor area, number of dwellings, year of construction, year of refurbishment, use type (building type), heating system type, annual electricity use, and annual natural gas use. The climate datasets are in the typical meteorological year (TMY).

The outputs are the urban energy consumption. It allows to perform retrofit analysis of existing buildings, urban planning, and visualizing the energy performance and code compliance status of building stock. The analysis includes drop shadows, thermal networks simulation, and/or optimization or renovation scenarios [22], [29], [30], [31], [32], [33].

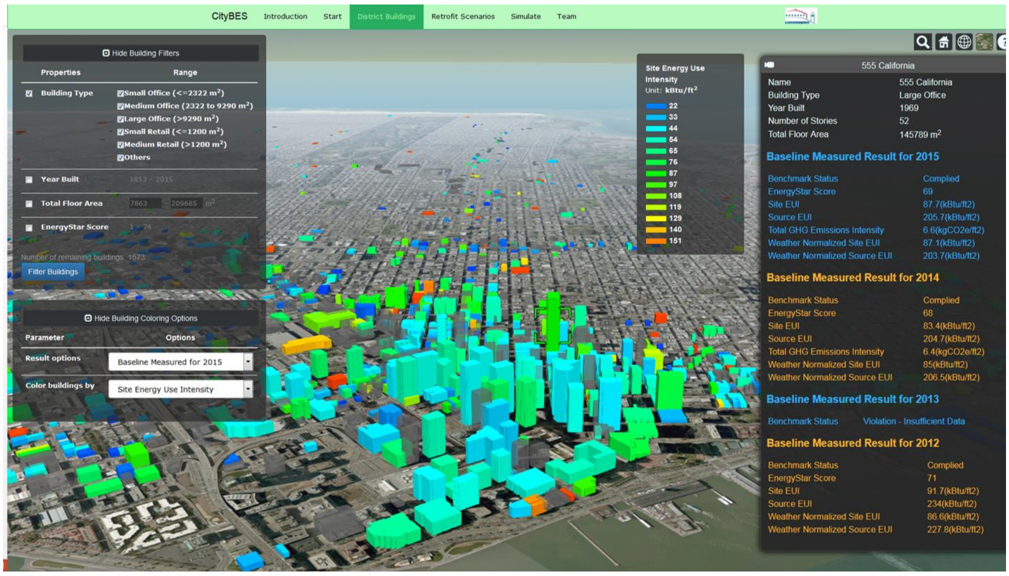


Figure 13. Example of CityBES dashboard [34]

3.2.2.1 Features

- ✓ Dataset. CityBES, directly integrated with a GIS, allows the use of both the CityGML and GeoJSON data formats. Being well integrated with CityGML, allow the use of Energy ADE. It is an extension of CityGML that helps running an urban scale simulation, since it includes further details of the buildings in addition to the ones available in standard geometry CityGML files, such as the thermal zones that compose a building, the building fabric, the occupancy conditions and the technical systems. It allows integrating a default dataset based on general characteristics of the buildings with their intended use and year of construction and other data provided by the user to adjust the characterization of the buildings. These advanced datasets are useful to easily run simulations on a large-scale.
- ✓ Variable Scale. CityBES is optimized to run simulations on a large scale, from district to city-scale. It offers building energy modeling and analysis at a city scale, with various retrofit scenarios considering a collection of 100 building technologies with performance and cost data for hundreds of thousands of buildings in U.S. cities including Boston, Chicago, Los Angeles, San Francisco, Washington D.C., San Jose, and New York City.
- ✓ It compares different scenarios of energy efficiency strategies, allowing also the evaluation of Green House Gas (GHG) emissions. In particular, CityBES is provided with 75 different strategies to be compared and evaluated including building envelope, HVAC and lighting.
- ✓ The time could increase exponentially if the analysis includes drop shadows, thermal networks simulation, and/or optimization or renovation scenarios but CityBES, based on an on-cloud platform, overcomes this limitation running the analysis on a server.
- × The development of a project needs to be upload to the LBL server, thus although it is a free tool, it is not fully standalone (it requires the interaction with the developer's team) [22], [29], [30], [31], [32], [33].

3.2.2.2 Applications

Currently, CBES supports the analysis of office buildings and small-to medium-sized retail buildings in several U.S cities, including San Francisco. Creating the building dataset is the first step for the city-scale retrofit analysis. Information was drawn from a range of sources to create the building dataset.

For this case study, a subset of the SF 3D city model was created with the buildings in the six selected districts. Five individual ECMs (energy conservation measures) covering three major building systems (lighting, HVAC, and envelope) that are commonly used in the U.S. commercial building retrofitting projects were selected for the retrofit analysis. Within the five ECMs, three are HVAC measures including space cooling efficiency, heating equipment, and air-economizers (which use more outdoor air if it favors free cooling rather than mechanical cooling); the fourth ECM is a lighting upgrade to LED; the fifth ECM is a retrofit to high-performance windows. For the heating system upgrade, the gas furnace (for small-sized office and retail buildings) and gas boiler systems (for other building types) are included in the retrofit analysis. For the cooling system upgrade, which depends on building type and vintage, the packaged single zone rooftop unit (for small-sized office and retail buildings), packaged multi-zone VAV rooftop unit (for medium-sized office and retail buildings), and central VAV systems with chillers (for large-sized office buildings) are considered. For the windows and lighting measures, single total cost-per-unit values are used. For the HVAC-related measures, the cost values of several capacities are provided. If the capacity of the retrofitted equipment falls within a range, a linear interpolation is used to obtain the total cost-per-unit of the equipment. If the capacity of the equipment is smaller than the minimum capacity, the total cost-per-unit of the minimum capacity is used. If the capacity of the equipment is larger than the maximum capacity, the total cost-per-unit of the maximum capacity is used. Two ECM packages were created by combining the five individual ECMs. One ECM package combined the LED and the air-economizer measures, and the other ECM package combined all of the five individual ECMs. It should be pointed out that the case study is not designed to automatically select the ECMs and identify the optimal retrofit packages with various investment criteria (e.g., energy savings, energy cost savings, GHG reduction, and payback).

CityBES was used to automatically generate the UBEM and run all simulations using EnergyPlus. After downloading the retrofit results in the CSV format, the energy-saving potential of individual ECMs, as well as the ECM packages for the 940 buildings, was evaluated. Therefore, is calculated the annual site energy savings and CO2 reduction per building type and simple payback year for the individual ECMs as well as the two ECM packages. The results indicate that replacing lighting with LEDs and adding air economizers are the most cost-effective measures. Replacing lighting with LED saves the most energy—310.9 GW h annually, which is 23.5% of the total annual site energy consumption. Another output is the distribution of annual site energy saving and payback years for the two ECM packages. The package with LED lighting and economizer can save 17–31% (5th and 95th percentile) of site energy per building with 2.1–6.1 (5th and 95th percentile) payback years; while the package with all five EMCs can reduce 23–38% (5th and 95th percentile) of site energy per building with 6.3–33.8 (5th and 95th percentile) payback years. By contrast, the payback is long for upgrading HVAC systems due to the mild climate of SF. Based on the calculated magnitude of energy savings and cost-effectiveness, this study shows that SF and its supporting utility company would obtain the most energy savings by providing incentives and rebates for upgrading lighting to LED and adding air-economizers to existing HVAC systems that don’t have them. It should be pointed out that the payback years of some ECMs are beyond their lifespan (e.g., gas boiler upgrade), indicating that those ECMs are not cost-effective in the SF climate. To estimate the impacts of shading on building energy use, another set of simulations were run without modeling the neighborhood buildings as shading surfaces. The adiabatic boundary conditions were maintained for the adjacent walls. This simulation showed that the case that did not model shading buildings overestimated retrofit savings. These results indicate that it is very important to consider the impacts of shading from neighborhood buildings on the UBEM energy performance, especially for the retrofit analysis [20], [21], [31].

3.2.3 CitySim

Built on top of the CitySim Solver, developed at the Solar Energy and Building Physics Laboratory of EPFL (Ecole Polytechnique Fédérale de Lausanne) CitySim Pro is a Graphical User Interface aiming at the simulation and optimization of the sustainability of urban settlements. It allows energy simulation at an urban district scale for urban form optimization and retrofits analysis [35][36].

3.2.3.1 Features

- ✓ Simplicity. CitySim uses its simplified simulation engine with optimization of urban form for cooling and heating demand calculation.
- ✓ Characterization. It allows integrating a default dataset based on general characteristics of the buildings with their intended use and year of construction and other data provided by the user.
- ✓ Easy weather. CitySim is able to extract a weather dataset in lots of readable formats automatically for the set location.
- ✓ Transport. It is integrated with the Multi-Agent Transport Simulation toolkit (MATSim-T Community, 2019) to perform transport analysis [35][36].
- × The domestic hot water and electricity use are not addressed directly as outputs.

3.2.3.2 Applications

CitySim's core models were applied to a group of buildings in the district of Matthäus in Basel (Switzerland). For this, a 3D model provided by the city's Cadastral Office was used and the physical description of the buildings was completed by means of the national census data for the year 2000 and results from a recent visual field survey of the district. Using the buildings' construction date, renovation status and with the help of renovation specialists (EPIQR Rénovation), they attributed the physical characteristics relating to the walls, roofs and windows [35][36].

3.2.4 TEASER

TEASER (Tool for Energy Analysis and Simulation for Efficient Retrofit) allows for fast generation of archetype buildings with low input requirements and the export of individual dynamic building simulation models for AixLib and other open-source Modelica libraries. These libraries all use the framework of the Modelica IBPSA library. TEASER is being developed at the RWTH Aachen University, E.ON Energy Research Center, Institute for Energy Efficient Buildings and Indoor Climate. This software is work-in-progress.

Documentation will be incomplete or missing and the software may not run properly. In particular, the Graphical User Interface is a beta release and not fully tested. It uses Modelica libraries that are based on the reduced-order calculation method and uses CityGML, for modeling and exchange of 3D city models [37][38].

3.2.4.1 Features

- × Even for TEASER, the domestic hot water and electricity use are addressed directly as outputs.
- × It is not equipped with automatic interfaces for the visualization of the results on the 3D geometry.
- × It allows simulation on different scales, however, to consider urban energy systems the tool should be used at least at the neighborhood scale.
- ✓ TEASER adopts simplified calculation approaches.

It offers a city-scale analysis and energy supply by district energy systems; a case study for about 3000 buildings in German cities with combined heating and power plant was provided [37][38].

3.2.4.2 Applications

The use case is a CityGML example file from Bad Godesberg, Bonn in Germany (Bezirksregierung Köln 2016). This file contains 2,897 buildings or building parts (e.g. terraced houses). First, the CityGML is imported into TEASER; building parameters are set according to the function. This data set provides no information about construction year, function, or a number of floors. Therefore, the year of construction and function are set to random parameters. The work team estimates the height of each floor. With this estimation and the height of the building, the number of floors is calculated. With the help of the BuildingsPy package, the simulation of all buildings starts automatically. The export module saves the extended data set into a valid CityGML file, with the use of the EnergyADE.

The main result of this work is a flexible process to generate dynamic simulation models in Modelica. However, it is a case study that does not intend to show reliable simulation results. Due to the unknown year of construction and function of the building, the uncertainty in simulation results would be massive. However, the main finding of this use case is that the tool is capable of handling a large number of buildings. Loading the CityGML file into the binding classes accounts by far the largest proportion share on time consumption. However, taking the number of buildings into account, this is still acceptable [37][38].

3.2.5 SimStadt

SimStadt is a software environment and homonymous former project at the University of Applied Sciences Stuttgart (HFT Stuttgart). The SimStadt software is the result of the homonymous project and it was successfully concluded in 2015. This platform aims to provide support for urban planners and managers for the definition and coordination to develop a modern city with low carbon emissions. [39][40]

3.2.5.1 Features

- ✓ Input. SimStadt is directly integrated with a GIS and it uses the City Geography Markup Language (CityGML). Being well integrated with CityGML, allow the use of Energy ADE. The latter leads it to have advanced datasets, useful to easily run simulations on a large-scale. Differently than CityBES which runs the simulation with EnergyPlus, it uses simplified methods.

- ✓ Scale. SimStadt, in its current state, is capable to manage and process data of the actual urban situation and future planning scenarios. Such scenarios include monthly and hourly energy demand analysis of single buildings, city quarters, entire cities and regions. It is well integrated with CityGML and Energy ADE, thus, it is easily exploitable for simulation from the neighborhood-scale to the city-scale.
- ✓ Output. It compares different scenarios of energy efficiency strategies, allowing also the evaluation of Green House Gas (GHG) emissions. [39][40]

3.2.5.2 Applications

In the framework of a project on the administrative district of Ludwigsburg, an Energy action plan was conducted to identify and plan CO2 emission savings, based on the available 3D CityGML city models. For this purpose, different workflows of the urban energy simulation platform SimStadt have been used and combined to assess the actual heating demand and the related CO2 emissions per building, predict energy savings potential following different refurbishment scenarios, and identify the solar energy potential. For the whole studied area, it was calculated the total yearly heating demand (3.9 TWh) and the average specific heating demand per year (145 kWh/m^2.yr). Considering the heating system distribution available for each municipality (from census data survey), they also evaluate the Megatons equivalent CO2 per year (0.92). Comparison with the calculated natural gas consumption showed deviations varying from 2% to 31% depending on the data availability and quality. For the photovoltaic potential analysis, were selected only suitable roofs for the panels. It was calculated how much energy per year all the roofs can generate and the percentage of electric demand which the PV energy can cover among the administrative district (for building electrical appliances) [39][40].

3.2.6 CityEnergyAnalyst (CEA)

The City Energy Analyst (CEA) is an urban building simulation platform and one of the first open-source initiatives of computation tools for the design of low-carbon and highly efficient cities. The CEA combines knowledge of urban planning and energy systems engineering in an integrated simulation platform. This allows to study the effects, trade-offs and synergies of urban design options and energy infrastructure plans. The latest version of CEA offers tools for the analysis of the carbon, financial and environmental benefits of the following strategies:

- Building Retrofits: appliances and lighting, building envelope, HVAC systems (incl. control strategies).
- Integration of Local Energy Resources: renewable and waste-to-heat energy sources.
- District Energy Networks: decentralized and centralized thermal micro-grids and conversion technologies.
- Modifications to Urban Form: new zoning, changes in occupancy and building typology [41][42].

3.2.6.1 Features

- ✓ Area. Is directly integrated with a GIS. Being a plug-in for ArcGIS is able to directly analyze the data from GIS databases, when available.
- ✓ Easy. CEA has an easy interface to work with them and it is possible to directly understand the effects of changes on the building stock. CEA, differently than CityBES that run the simulation with EnergyPlus, use simplified methods.
- ✓ Most versatile scale. City Energy Analyst offers energy demand/supply analysis for buildings at a district scale to support decision making of energy efficiency planning. CEA seems to be the most versatile tool, easily allowing simulations from the block-scale to the city-scale.
- ✓ Resource potential. CEA has the most advanced model that considers the ambient heat potential (e.g. geothermic, lake water and source of waste heat) and solar potential.
- ✓ LCA analysis. Compare different scenarios of energy efficiency strategies, allowing also the evaluation of Green House Gas (GHG) emissions. CEA is provided with a tool to perform a cost-benefit analysis of the applied strategies to provide an economic point of view in the evaluation of scenarios [41][42].

3.2.6.2 Applications

The CEA team tested the CEA framework in a real case study in the Swiss city of Zurich. It consists of an industrial site of 25 ha undergoing a process of urban transformation. A large manufacturer in the industry sector owns and predominately occupies the site along with other companies in the services sector. At the moment, there is no residential use on site. Departing from today's condition or Status Quo scenario (SQ), a past research project developed four different retrofit scenarios for the area by 2035. Many other projects have been developed by CEA's teamwork in Zurich and Singapore. Moreover, other new locations will be involved, like Amsterdam [42].

CEA has also been applied to the university district in the center of Zurich, which is home to three world-class institutions in research, education and health: ETH Zurich, the University of Zurich and the University Hospital Zurich. The area is being redeveloped as an internationally competitive location for knowledge and health with an increase in usable floor space of 40%. In order to realize this growth and redevelopment in a dense urban area, the interests and demands of the three key stakeholders have to be considered and coordinated. ETH, University and Hospital must explore the potential synergies for sharing land and services, balanced with the use and expansion of green spaces that are of great relevance for the area. The CEA is used in the EU ERA-Net project *SPACERGY* to analyze the effect of urban planning measures on the Hochschul quartier's energy demand in terms of quantity, quality (temperatures) and dynamics. Furthermore, the CEA will be used to define the necessary infrastructure for developing new energy sources and demands to a century-old distribution network[42].

Another CEA study in Zurich includes over 5,960 individual buildings where over 84% are either residential or mixed-use residential buildings primarily built between 1920-1975. The forecasts of energy demand and solar photovoltaic (PV) generation of CEA are used as input data for an agent-based model to simulate the adoption of individual and community solar PV systems. The agent-based model analyses how the geographical location of households, their environmental attitudes, their interactions, and the prices of electricity and solar PV systems interact with the new ZEV (Zusammenschluss Zum Eigenverbrauch) regulation. The research goal is to explore the evolution of solar PV adoption for such urban quarters in Switzerland[42].

CEA was applied to Singapore, with the aim of obtaining the demand forecast and to build a district energy systems optimization. Singapore's biggest ship terminal will be transformed into a potential high-density, mixed-used city quarter by 2030. The CEA is used to study synergies between buildings and the district energy infrastructure for the site [42].

For example, the Nanyang Technological University (NTU) Singapore's EcoCampus Initiative aims to be a leading example of high impact energy efficiency and sustainability for urban developments in Singapore. The goal is to achieve a 35% reduction in energy, carbon, water and waste intensity. The initiative encompasses the NTU Campus as well as new developments in the neighborhood. The CEA is used in the RD&D Project *Urban infrastructure optimization for Eco-Campus project* together with industry partner VEOLIA for energy demand and emission forecasting for the campus in 2020 and spatial visualization of supply systems choices to support the decision making process for the optimal choice of energy supply technologies for the future[42].

Finally, CEA was applied to Amsterdam's metropolitan area, which faces an explosive population growth over the next twenty years. Within this expansion, the Municipality of Almere will realize the largest portion of new developments, including 60 000 new homes. Almere has the ambition of increasing its size while also increasing the quality of life for its inhabitants, including ambitious plans regarding sustainability. The legacy of the site of Floriade 2022 (the world's largest horticultural expo) in Almere, will be co-developed as a green extension to the city center with the theme 'Growing Green.' The proposal creates an energy-neutral, mixed-use residential area that directly integrates a grid of 'gardens' into the built environment. The CEA is used in order to analyze the effect of building form and vegetation on the area's energy demand in terms of quantity, quality (temperatures) and dynamics[42].

3.2.7 Comparison summary

A comparison among the tools descripted can be summarize focusing on which input and output that they can elaborate, so which stakeholders that they can involve.

3.2.7.1 Inputs

As explained in the previous sections, the more input a tool requires, the more accurate its analysis can be. Regarding geometry input, all the tools work with a manual 3D mapping while CEA, SimStadt, CityBES and TEASER use the GIS spatial dimension. Each tool manages the building characteristics in a different way and allows to deepen some topics and overlooks others. However, all tools allow the user to upload a weather dataset in lots integrated with Multi-Agent Transport Simulation toolkit of readable formats (e.g., epw, txt, ddy, etc.). Only CityBES and CEA have an easy interface to work with the energy targets to be achieved and it is possible to directly understand the effects of changes on the building stock.

3.2.7.2 Outputs

On the other hand, outputs show mainly the energy demand of the area. All the tools provide building use related data, such as energy use for heating/cooling, system, electric energy use and energy use for domestic hot water. Only UMI provides the daylighting with CitySim. However, CitySim together with TEASER is not able to calculate electric energy use and energy use for domestic hot water. About the resource potential, all the tools analyzed to calculate the solar potential except CitySim and only CEA integrates the environmental energy potential. Looking at the urban system, CityBES offers the district heating/cooling integration while CEA considers the energy network; TEASER integrates both. A large-scale general evaluation shows that CEA is the most complete because it gives a scenario evaluation, GHG emissions and a cost-benefit analysis. CEA only misses the transport/mobility sector, which, on the other hand, it is the only general evaluation that UMI and CitySim can support. Spreadsheets and graphics as a kind of output belong to all the tools selected [21].

3.2.7.3 Stakeholders

Policymakers, designers, modelers, so engineers, and researchers interested in the comparison of different energy conservation measures, could use the results of CityBES, CEA and SimStadt. Especially the first two, already integrate numerous energy conservation measures in the form of databases and allows automatic comparisons between scenarios. Also, in the perspective of a low-carbon future, the results of SimStadt, CityBES and CEA can be used to assess the GHG emissions of urban areas. This could be a fundamental step for policymakers that want to design new policies or measure the effects of existing ones. All the tools require a sound experience in energy modeling to provide meaningful output [21] [22].

On the other hand, TEASER, that is well integrated with the design of urban energy systems, could be used by designers and managers of systems and by distribution and transmission operators. UMI is well developed to analyze relatively small areas such as neighborhoods, in fact, it allows a detailed overview of the energy needs of buildings, daylight analysis, solar potential and walkability. Its results could be used by municipalities to optimize new and existing urban areas. Moreover, its dependency on Rhinoceros and such a level of detail could more direct UMI to the architect's category [21][22]

However, depending on the complexity of the engine used to run the energy simulation, some specific technical knowledge could be required. Each tool is characterized by a GUI that can facilitate the modeling for users not highly skilled in urban energy simulations. CityBES is very well developed for the nine cities available on the website, and the developing team supports users with new case studies, allowing also to people with little knowledge of the tool to analyze their cases. CEA and CityBES are characterized by the simplest GUI, however, the CEA user is freer to start new case studies and to create advanced analysis, and thus, energy modeling knowledge is necessarily needed. UMI does not have a dedicated GUI, but it is accessible via Rhinoceros and Grasshopper interfaces, thus knowledge of these tools is required. CitySim and SimStadt are characterized by a GUI based on BES software, thus, is oriented to users with general knowledge of simulations. TEASER is the most demanding one, even if it allows a simple characterization of buildings through the *data enrichment* function. Good knowledge of urban energy systems is required to exploit the tool at its full potential [21] [22].

3.2.8 Choice of tool

The Bottom-up category, which includes all the tools mentioned, is the one that was first selected, since it includes the tools that may better evaluate scenarios for current and future district management and design. In fact, starting from a single building scale , they can aggregate the results and give an accurate simulation. Apparently, every tool could seem to be adapt for the thesis aim, since they all support a kind of energy use for the single building, i.e. for heating/cooling. However, the high heterogeneity of the features makes this choice more crucial. Several strong points may be evaluated for each tool, for which they become more suitable for a specific audience (stakeholders) category rather than another (table 2).

Table 2. Tools strengths and audience summarized

	CityBES	UMI	TEASER	CitySim	Simstadt	CEA
Strengths	Open source, high developed, Web-based, assess the GHG, friendliest GUI (low knowledge needed), energy conservation measures in the databases [22][21]	Accurate for districts (walkability, bikeability etc.)[22][21]	Simple characterization of buildings [21]	Transportation management , minimize energy usage [22][21]	Assess the GHG, detailed database [21]	Open source, optimization of energy systems in city and district scale , assess the GHG, energy conservation measures in the databases, renewable source potential. [22] [21]
Audience	Policymakers, urban planners, city managers, building owners, researchers[34][21]	District energy managers[22]	Urban planners, district managers, distribution and transmission operators, single end-users [22][21]	Policy makers, urban planners	Policymakers, designers, urban planners and researchers[21][22]	Policymakers, designers, urban planners and researchers[21][22]

Clearly, the best choice should have been a tool which as skilled as possible, in order to have the most accurate modelling and planning, exploiting all the opportunity that the UBEM may give. According to more analysis, the most skilled and developed tools in general are CEA and CityBES, but also UMI shows good performance for the district scale especially. They basically give more outputs compared to others.

Among them, UMI offers beyond the standard functions, many further skills, like the level of walkability, bikeability, daylight and so on. Also, beyond the several applications in USA, Boston, there were as well 4 applications in Lisbon between 2016 and 2017. It is based on the simulation engine EnergyPlus which allows to a run very detailed analysis. However, it has some limitation being a desktop-based software, contrary to web-based software, more performant (CityBES) or tools which use simplified methods (CEA). So, CityBES seems to offer the same power of UMI conferred by EnergyPlus, but with higher performance and development, tending to overshadow UMI. Moreover, the CityBES developer team's support could have been essential with any doubt.

On the other hand, there is City Energy Analyst, which competes with CityBES for all the outputs available and a GUI same intuitive. They both integrate numerous energy conservation measures in the form of databases and allow automatic comparisons between scenarios. Additionally, CEA has the hugest range of outputs available and it can make a very advanced analysis. Especially, it can consider the ambient heat potential (geothermic, lake water, source of waste heat) and solar potential. Involving most of the renewable solutions, this skill allows to manage properly the NZEB goal. Furthermore, at last but not least, CEA is the one that is real open source, with its own free dashboard.

Thanks to its flexibility in use and solutions, especially suitable for the district scale, the tool chosen for this thesis is therefore CEA.

4 Vale the Santo Antonio District analysis in CEA

A comparison between the current and a future CEA scenarios will be the key topic with which it will be possible to understand how to improve, or rather how to get closer to the target, the net-zero energy condition on the system.

First, what is required is a representation of how the actual VSA is composed with an accuracy as high as possible. The accuracy level it depends on the data availability, beyond on the CEA ability to perform the simulation. The criticality of these tool comes immediately out when the scenario is created, when a lot amount of architectural and energy data is required. The data availability become particularly limited in the district topic, since no specific source is normally dedicated to this scale of detail, higher than one for a country's analysis, but inevitably lower than one for the building modeling. In this regard, VSA gives a big advantage thanks to the already existing project by the Lisbon Municipality Chamber, VSA urbanization plan (PUVSA)[10], which allows to provide many data required for the simulation.

However, a lack of data is still existing, thus other source of collection are necessary. The rest of the information is taken from a more general data collection for Lisbon houses, according to ADENE[43]. A further extension of the comparison scale, with so an accuracy reduction, is made providing data from the Portugal average features. Furthermore, we must premise that, even with a total data availability several geometrical and weather-related features, like the houses' orientation and height, the sun exposure, the roof shape, and other crucial details, are not so representative due to the limitations of the tool.

In the next paragraph will be introduced the district archetypes, the description of the values and how they were provided

4.1 District energy planning - Current scenario

4.1.1 Archetypes definition

4.1.1.1 Zone

The zone is just selected through the location search engine, in the first step, when the whole scenario is created. First, a perimeter shape is drawn on the map, and all the buildings contained are evaluated for the rest of archetypes; the buildings just outside the perimeter are part of the surroundings.

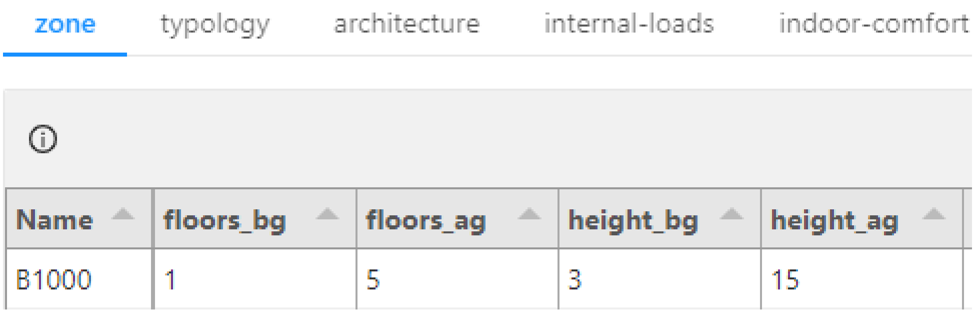
Figure 14. Vale Sant Antonio figured in the CEA dashboard

4.1.1.2 Floor, Height

After the creation of the shape scenario zone, all the building floors and heights above ground are calculated automatically, provided from GIS databases, the Geographic Identity System. In a matter of seconds, we get a complete digital replica of buildings and streets in the area of interest, including information about years of construction, usage, floor area and more.

Figure 15. CEA building selected

In parallel, we can obtain metadata about energy systems, carbon emissions, and costs. However, these further data is available only in Switzerland and Singapore, where the software was implemented, so a meaningful model of VSA needs various database changes.



Name	floors_bg	floors_ag	height_bg	height_ag
B1000	1	5	3	15

Figure 16. CEA dashboard, zone input

4.1.1.3 height floor value

Height floor values are very similar among building types across the years. According to the ADENE [43], the average value remained around 2.6 mt. However, each building has its own accurate value, given by the GIS.

4.1.1.4 Floors/Height below ground

It is pre-selected 1 floor for every building and 3 meters as height below ground. The default values assigned from CEA can be kept since in Lisbon the houses with a basement are quite spread.

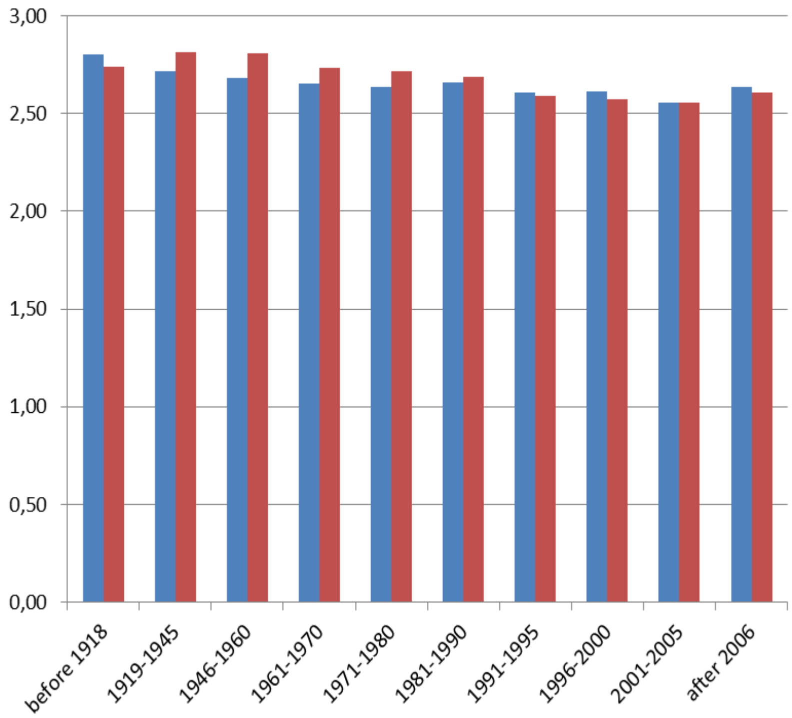


Figure 17. Average Lisbon height floor per construction period and type (buildings in blue, multi-family buildings in red; ADENE)

4.1.2 Typology

For typology, CEA means several features related to the building characteristic.

4.1.2.1 Year

Among the 83266 buildings from Lisbon Municipality, the highest share of buildings is from 1946 to 1960. A higher number of single buildings (in blue) until 1970, exception made for buildings after 2006 (Figure 18).

Thanks to an Archetypes map of the neighborhood provided by the municipality [9] (figure 19), all the current buildings can be dated correctly. The district does not follow the previous Lisbon survey; indeed, we can note that the highest number belongs to 90’ buildings (multi-family). There is still, however, a wide presence of the oldest buildings from the 20’-40’. For each gap shown by color (figure 20) it is selected the lowest value to be as conservative as possible. Normally, the older a building, the stronger the measures to be taken. Therefore, from the figure : 1920 (blue), 1945 (orange), 1960 (light blue), 1990 (yellow), 2005 (green).

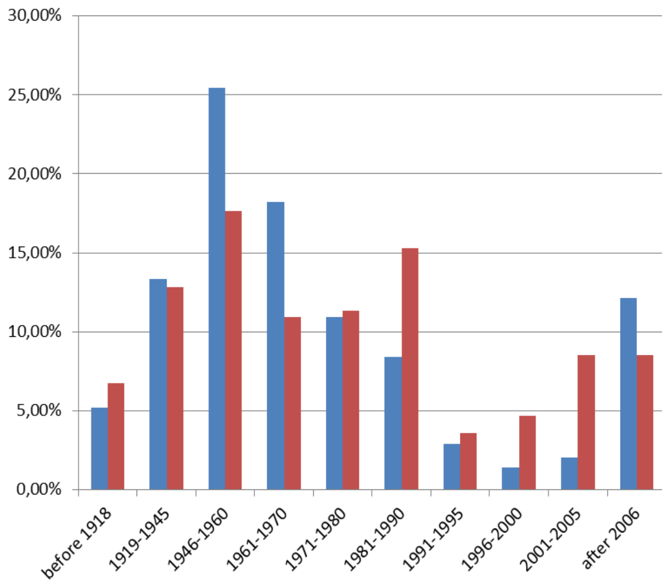


Figure 18. Lisbon construction period rate (buildings in blue, multi-family buildings in red; ADENE)

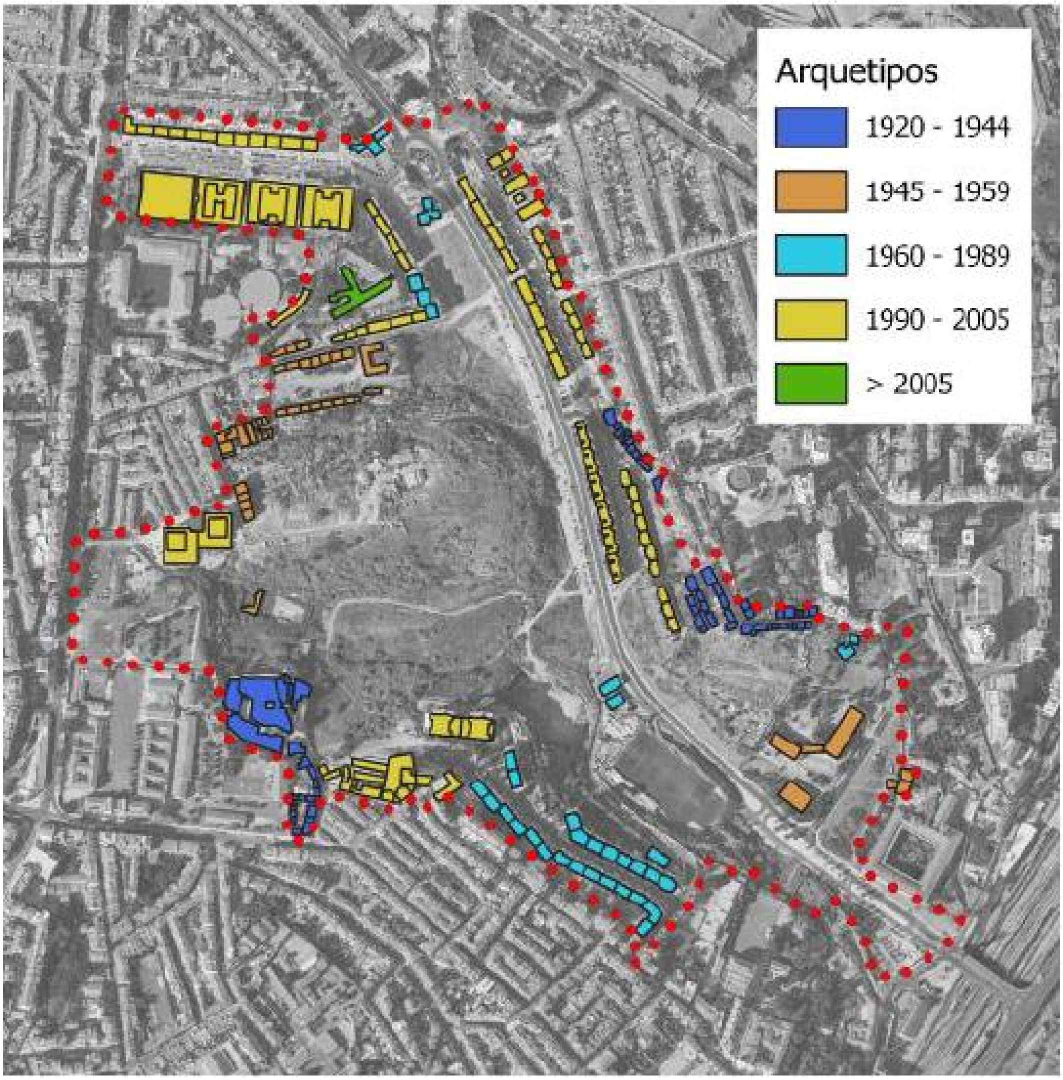


Figure 19. Map of VSA buildings colored by period of construction [10]

4.1.2.2 Construction Standard

A simple and useful identification with the STANDARD (STD) methodology is adopted by CEA. All the archetypes are linked to a different number of STD; each standard is made of a different combination of characteristics and automatically provides a customized profile for each building, based on the standard number (ex. STD 1, STD 2, ic.). CEA also provides an association year-standard number (e.g. 2010-2020 has standard 6) and there is followed for the model. Nevertheless, since these standard packets are made for Swiss and Singapore, they must be modified. There are basically two possibilities to set the archetypes data: editing the database provided that automatically can be mapped on the entire scenario (database editor), or, directly editing on the archetypes screen every single building (input editor, figure 21), regardless of database archetypes mapping.

The construction standard identification, according to the CEA year-standard association, is: 1920 (STD 1), 1945 (STD 2), 1960 (STD 2), 1990 (STD 4), 2005 (STD 5).

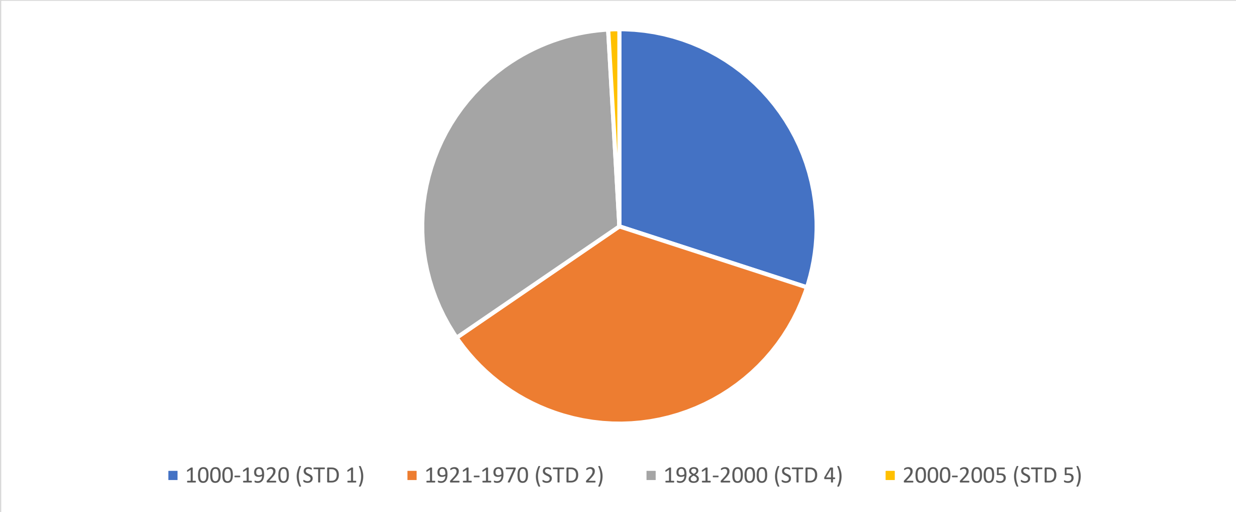
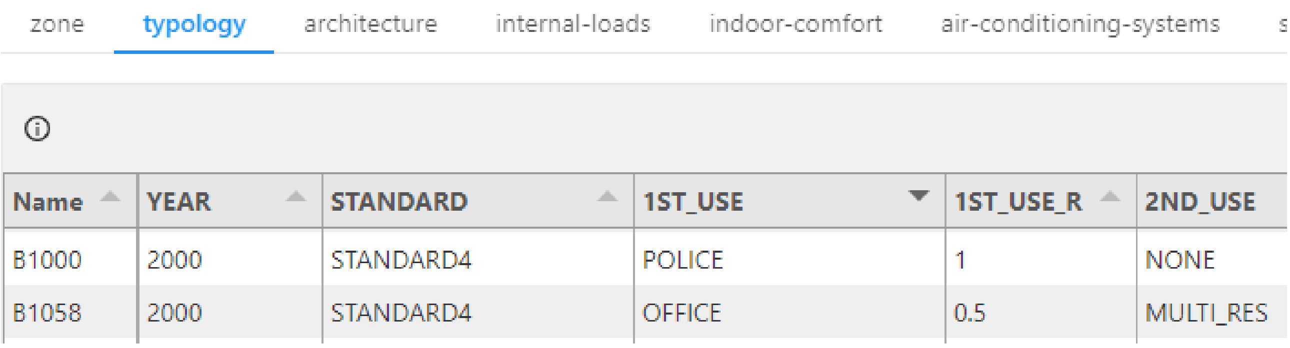


Figure 20. Distribution of VSA buildings for period of construction

4.1.2.3 Building type

In VSA the tool recognizes 110 constructions in total. Most of them are evaluated as multi-residential buildings (106). However, the service sector, which includes only a small part of buildings, includes schools (3) restaurants (3), office buildings (2), library (1), food store (1) and police station (1). An additional level of detail is conferred with the typology subdivision for each building. There are therefore up to 3 typologies (or use) per building. The ratio input for each use is also available, however, still little in the overall budget, given the net majority of residential-only complexes.



Name	YEAR	STANDARD	1ST_USE	1ST_USE_R	2ND_USE
B1000	2000	STANDARD4	POLICE	1	NONE
B1058	2000	STANDARD4	OFFICE	0.5	MULTI_RES

Figure 21. CEA dashboard, typology input

4.1.3 Architecture

In this section, we deepen the architecture topic, with values kept in accordance with the default standard number. Most of them follow the Swiss default setting:

- The number of floors (from the ground up) with an open envelope = 0 (default);
- Fraction of gross floor area with electrical demands = 0.82 (default);
- Fraction of above-ground gross floor area air-conditioned = 0.82 (default);
- Fraction of below-ground gross floor area air-conditioned = 0.4;
- Fraction of net gross floor area = 0.82 (default);

- Window to wall ratio in facades facing = 0.21.

The fraction of the below-ground gross floor area air-conditioned deducted larger than the default zero value since approximately half of the basement should be inhabited.

Every direction (North, east, south, west) for the Window to wall ratio has 0.21 for most of the building as default. Only the newest standard models (std 5) have 0.15. The ADENE data (figure 22) shows a window to wall ratio that stay constantly around 0.17 along the last century. The value increased year by year in the new millennium reaching 0.25 (average value among buildings and multi-family houses).

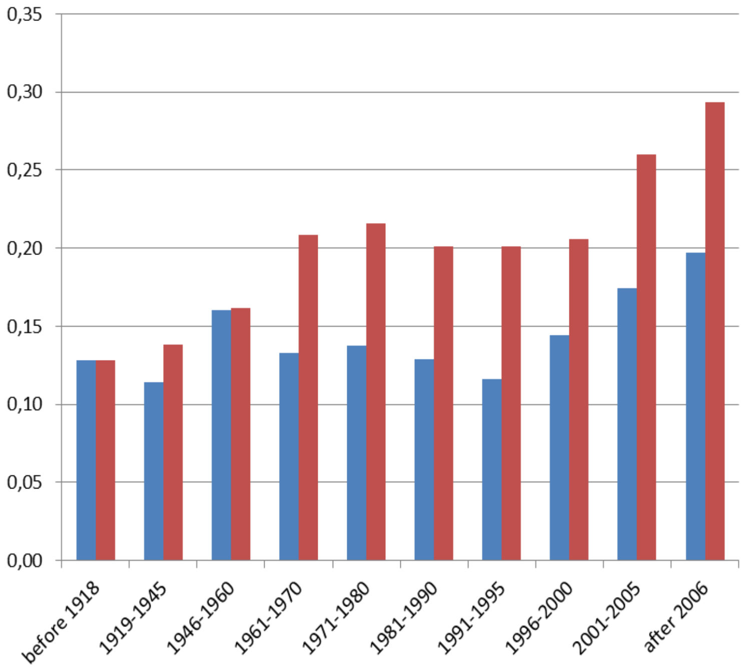


Figure 22. Average Lisbon wall ratio (ADENE)

4.1.3.1 Type of construction.

It relates to the contents of the default database of the Envelope Properties. The mechanism is still the same: selecting a code we can add a specific value collected in the database, of which typology depends on the setting. In this case, is chosen a construction level, "Medium construction" for standard 2 buildings, "Heavy construction" for STANDARD 1, 4 and 5. What we are changing is, in particular, the Internal heat capacity per unit of air-conditioned area (Cm_Af)[1].

- STANDARD 2 - Medium construction, Cm_Af = 165000 [J/Km^2];
- STANDARD 1,4,5 - Heavy construction, Cm_Af = 300000 [J/Km^2];

4.1.3.2 Tightness level

It represents the air exchanges per hour at a pressure of 50 Pa, [1/h], scale of values from 1 to 6.

- STANDARD 1,2,4 - Medium leaky, n50 = 4 [1/h];

[1] Defined according to ISO 13790

- STANDARD 5 – Tight, n50= 2 [1/h].

4.1.3.3 Roof construction type

In order to describe each part of the building, several factors[2] are considered such as:

- U: thermal transmittance of surface including linear losses (+10%);
- a: solar absorption coefficient;
- e: emissivity coefficient of external surface;
- r: reflectance coefficient in the Red spectrum. Defined according Radiance. (long-wave);
- GHG: embodied emissions per m^2 of surface. (entire building life cycle) [kg CO2-eq/m^2].

These factors are here associated to the roof surface, but they have to be applied for each other surface of the building. The availability of these values applied at the neighbourhood, especially for the roof, is not high. The most important factor, U value, is obtained for the Lisbon scale through the ADENE source. For the others, like the roof U value or the absorption, reflectance etc., a reliance on the CEA datasheet is necessary. However, for each element of the architecture database a cross-checking is possible and recommended, since also the materials are indicated.

Table 3. Roof construction datasheet

	U [W/m^{2}K]	**a**	**e**	**r**	**GHG [kg CO2-eq/m^2]**
STD 1,2 - Clay tiles, old construction	0.3	0.55	0.91	0.449	112
STD 4 - Concrete or rock pebbles finishing	0.2	0.6	0.94	0.4	112
STD 5 - Dark paint over plaster over concrete	0.15	0.85	0.94	0.15	112

4.1.3.4 Shading system type

The “rollo” typology belongs to all the buildings. A shading coefficient[2] (rf) makes the difference when shading device is active: rf = 0.08.

4.1.3.5 External wall construction type

Even for the wall, as for the ceiling, the same coefficients are considered. U value can be considered the most influential one, so it is equally necessary to compare it with collected data in order to be as accurate as possible.

[2] Defined according to ISO 13790

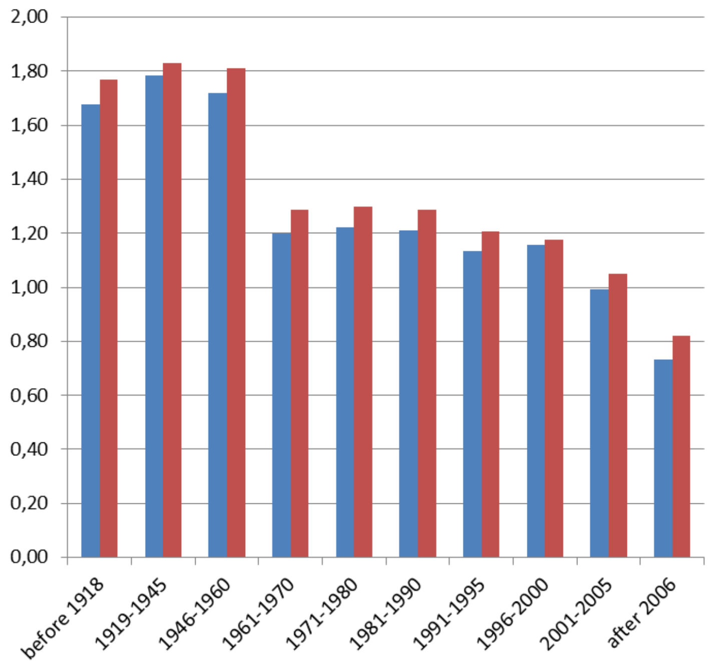


Figure 23. Average Lisbon wall U-value (ADENE)

Table 4.External wall construction datasheet

	U [W/m^{2}K]	**a**	**e**	**r**	**GHG [kg CO2-eq/m^2]**
STD1 - concrete block exposed - old building	0.75	0.6	0.95	0.4	112
STD 2,4 - White paint over plaster over clay brick - old building	0.1	0.3	0.9	0.7	112
STD 5 - Dark paint over plaster over concrete	0.7	0.85	0.94	0.15	112

4.1.3.6 Floor wall construction type

About this part, only two aspects matter: the usual U-value (thermal transmittance of floor including linear losses +10%) and the GHG:

- STANDARD 1,2,4,5 - concrete floor, U = 2.9 [W/m^{2}K]; GHG = 112

4.1.3.7 Basement floor construction type

- STANDARD 1,2,3,4,5 - concrete floor (basement), U = 2.9 [W/m^{2}K]; GHG = 247

4.1.3.8 Window type

Two further factors[3], F and G, are introduced. The first represents the window frame fraction coefficient / UNIT: [m^2-frame/m^2-window]. The second, G, is the solar heat gain coefficient. Even for the windows U is very important and the value is also taken from ADENE database.

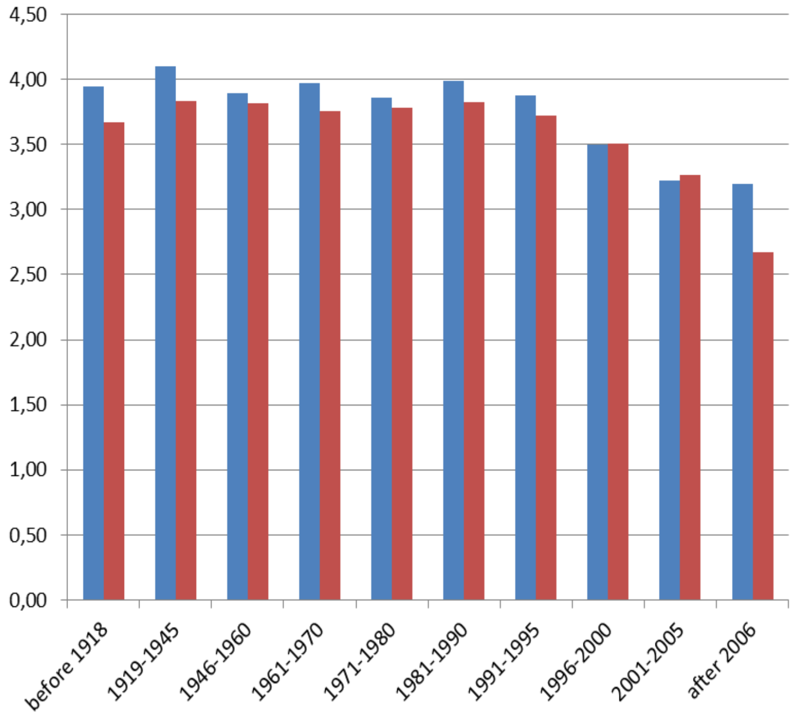


Figure 24. Lisbon windows U-value along the years (ADENE)

	U [W/m^2K]	G	e	F	GHG [kg CO2-eq/m^2]
STD 1,2 - single glazing	4	0.85	0.89	0.2	74
STD 4,5 - Double glazing	3.25	0.75	0.89	0.2	62

- STANDARD 2 - single glazing;
  U = 4 [W/m^2K]; G = 0.85 e= 0.89; F = 0.2 GHG = 47 [kg CO2-eq/m^2]
- STANDARD 4,5 - Double glazing;
  U = 3.25 [W/m^2K]; G = 0.75 e= 0.89; F = 0.2 GHG = 62 [kg CO2-eq/m^2]

4.1.4 Internal loads

The tool offers a long list of factors that are influential among the internal loads, in terms of energy consumptions and costs. In this case, is not the age of the building that matters, but the type of use. A big

[3] Defined according to ISO 13790

table can summarize most of the values, presenting the comparisons among the types, although the multi-residential is totally predominant.

Table 5. VSA internal loads (CEA database)

	School	Library	Foodstore	Office	Restaurant	Multi-res
Occupancy density: [m2/pax]	3	5	8	14	16	30
Peak sensible heat load of people: [W/pax]	70	70	70	70	70	70
Moisture released by occupancy at peak conditions: [gh/kg/p]	80	80	80	80	80	80
Peak specific cooling load due to refrigeration (cooling rooms) [W/m2]	0	0	0	0	0	0
Peak specific charging capacity per vehicle [kW/vehicle]	0	0	0	0	0	0
Peak specific process cooling load [W/m2]	0	0	0	0	0	0
Peak specific process heating load [W/m2]	0	0	0	0	0	0
Peak specific daily hot water consumption [lpd]	2	0	2	3	16.25	35
Peak specific freshwater consumption (includes cold and hot water) [lpd]	30	0	30	60	50.9375	140

4.1.5 Electrical loads

Table 6. VSA electrical loads (CEA Database)

	School	Foodstore	Library	Office	Restaurant	Multi-res
Peak specific electrical load due to computers and devices [W/m^2]	4	2	2	7	5	8

Peak specific electrical load due to artificial lighting [W/m^2]	14	6.9	21.3	15.9	4.8	2.7
Peak specific electrical load due to industrial processes [W/m^2]	0	0	0	0	0	0
Peak specific electrical load due to servers/data centers [W/m^2]	0	0	0	0	0	0

4.1.6 Indoor comfort

The setpoint temperatures for the heating systems are here chosen. Actually, electrical common devices normally used in Portugal's houses are often not automatically started according to this temperature. However, it should be meant as a temperature below which the thermal comfort begins to get lost, so with a room temperature below the following values, the heating system is switched on manually by the users. A temperature of 20 °C is chosen for the supermarket, 21 °C for the rest of the typologies.

The tool's default system offers another option, the Setback point. Actually, it is not an option for most of the Portuguese building since the heating system is essentially manually activated. This option could not be kept only for the high standard buildings standard or some type of use that has a centralized and a more updated heating system, like the standard 5 School.

The setpoint temperature for the cooling system, since it includes devices more technologically updated, can be meant like the actual setpoint of the device above which it starts to operate, 26 °C for every building. Above this room temperature, the cooling system starts to work. However, this option works only for the types that have the cooling system: offices, police, food store, library, and restaurant.

On the other hand, the setback point of temperature for the cooling system can be used, being the mini-split technology enough updated only for buildings with a cooling system. However, it is not considered as the economic resources on average low and the territorial natural ventilation normally strong.

The lower bound of relative humidity is set to 30 %, only the library has 40 %. The upper bound instead is 60 %, 70 % for the restaurant.

Always as preset by the tool, the indoor quality requirements of indoor ventilation per person, measured in l/s, is 6.94 at schools, 8.33 in multi-residentials and food stores, 9.89 in the restaurant and 10 in offices and the library.

4.1.7 Air conditioning-system

This section deeply describes each typology of the building's HVAC emission, which its own configuration of heating, cooling, and water supply system. Especially, it is possible to choose many options for setting the HVAC emission system.

4.1.7.1 Cooling supply system

The type of cooling supply system: in not considered for residential buildings and schools; Minisplit is used exclusively for restaurants, offices, and libraries since they are the most common devices currently; A more different air-conditioning system (Central AC) is used for the food stores.

4.1.7.2 Heating supply system

The type of heating supply system is a Radiator 90/70, which represents the closest option to the basic heaters present in the houses of Lisbon.

- Convective part of the power of the heating system in relation to the total power: 1
- Maximum heat flow permitted by cooling system per m2 gross floor area = 500 [W/m2]
- Nominal supply temperature of the water side of the sensible heating units = 90 [C]
- Nominal temperature increase on the water side of the sensible heating units= 20 [C]

4.1.7.3 Hot water supply

Type of hot water emission in the HVAC system is an “high temperature water”, which let supply water temperature reach typically 60 °C. The water Maximum heat flow permitted is set 500 [W/m^2].

4.1.7.4 Ventilation

About the type of ventilation strategy, a “window ventilation” surely respects the current option, therefore it includes all the buildings. The city’s weather file is significant in this job since the city is normally quite windy.

4.1.7.5 Heating and cooling season

Following, the general calendar (day/month) of the heating and cooling season. These dates don’t indicate that the systems are in use the whole period, but simply the period when each type, cooling or heating, is ready to be used. It is simply indicative of the transition period since the heating/cooling period cannot be overlapped in CEA. Looking at the Lisbon average temperature graph, the following calendar can give acceptable general results for most of the buildings. They are, anyway, quite conservative, since Lisbon houses would need much less heating/cooling degree days.

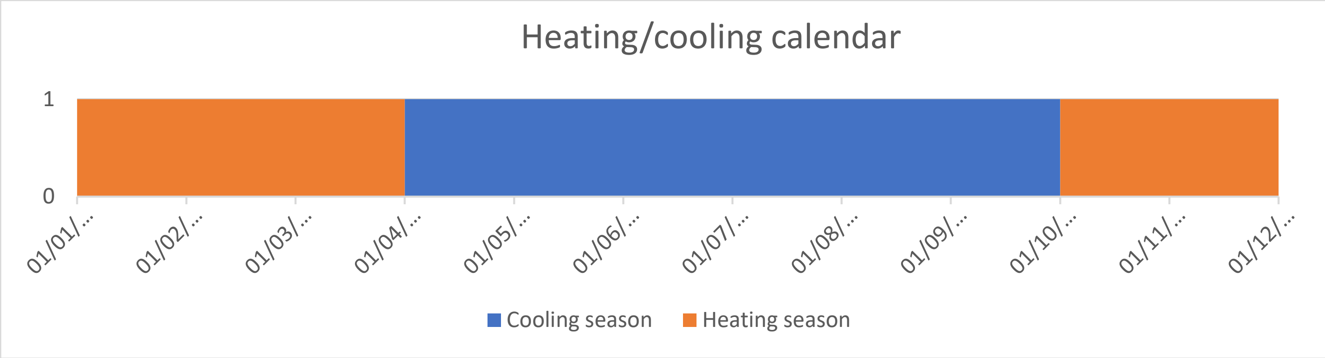


Figure 25.VSA Heating/cooling calendar (CEA).

4.1.8 Surroundings

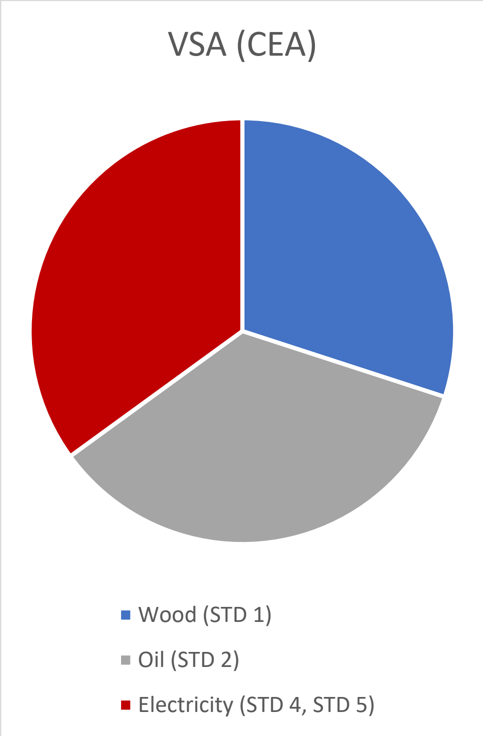
Everything related to the surrounding still based on the GIS. It applies for the "number of floors above ground (incl. ground floor)" option and "Height above ground (incl. ground floor)"

4.1.9 Supply system

In order to give an as real as a possible scenario, a comparison with reliable sources is necessary. Portuguese energy trends are deeply addressed by the 2010 INE report about the distribution of domestic consumption by source type.

4.1.9.1 Type of heating supply system

Wood feedstock looks predominant in the ambient heaters market, followed by the Diesel and the electrics. The voice GPL includes more types such as GPL Butane, GPL Propane, GPL channeled [18].



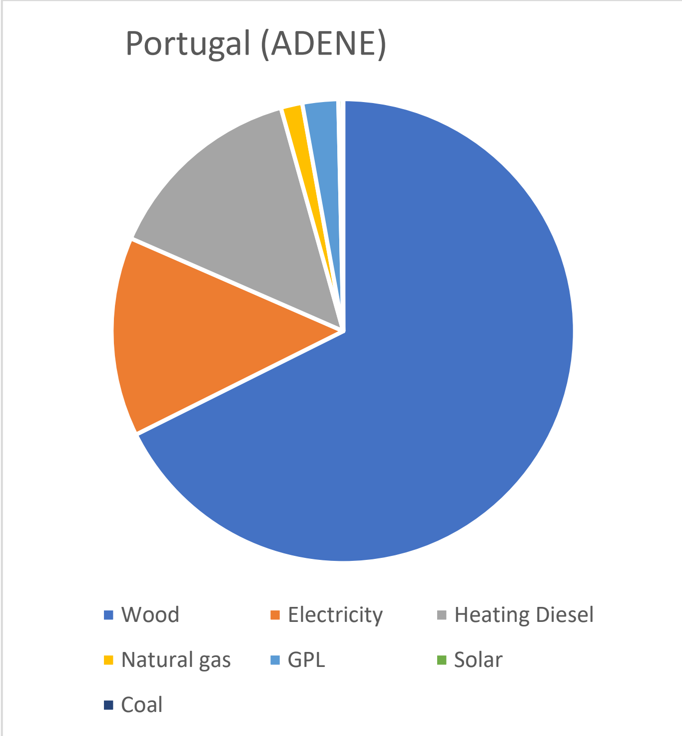


Figure 26. (Left) VSA supply for heating energy by source (CEA)

Figure 27. (Right) Distribution of VSA supply for heating energy by source (approximation done from the ADEDE data)

However, these data have to be contextualized in the current scenario, since they are 10 years old and they represent the whole country and not Lisbon. So, for electricity, from use of just 13 %, a shift was made on 35, representing all the upper classes, STD 4 and 5. While the other sources are wood (30%) and oil (35%), which replaces Diesel since they can be compared in terms of efficiency and emissions. In addition, the CEA feedstock list is limited, so GPL and Diesel are not available.

The electrical boiler for STD 4 and 5, with these features:

- efficiency of the all in one system: 0.9;
- capital costs per kW: 200 USD2015/kW;
- lifetime of this technology: 20 years;
- operation and maintenance cost factor (fraction of the investment cost): 1%;
- interest rate charged on the loan for the capital cost: 5%.

The Oil-fired boiler for STD 2, with these features:

- efficiency of the all in one system: 0.8;
- capital costs per kW: 493 USD2015/kW;
- lifetime of this technology: 20 years;
- operation and maintenance cost factor (fraction of the investment cost): 1%;
- interest rate charged on the loan for the capital cost: 5%.

The wood furnace for STD 1, with:

- efficiency of the all in one system: 0.6;

- capital costs per kW: 200 USD2015/kW;
- Lifetime of this technology: 20 years;
- Operation and maintenance cost factor (fraction of the investment cost): 1%;
- Interest rate charged on the loan for the capital cost: 5%.

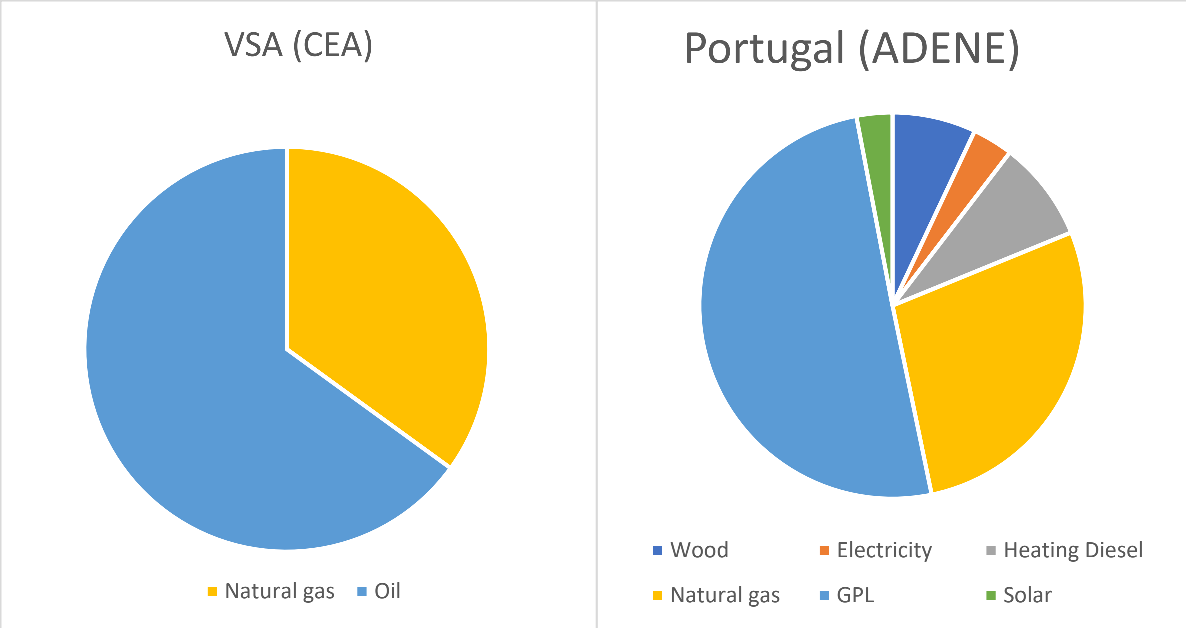


Figure 28. Distribution of VSA supply for water heating by source (left)

Figure 29. Distribution of Portuguese energy consumption for water heating by source (right)

4.1.9.2 Type of hot water supply system

Regarding the water heating, Portugal in 2010 presented a huge percentage of LPG consumptions, namely domestic LPG bottles. Even in this case, a substitution is made with normal Oil instead of LPG, covering also the percentage of Diesel; other types like solar and electricity are rarer, so neglected. Natural gas presents a percentage quite similar.

Natural gas-fired boiler for STD 4 and STD 5 presents these features:

- efficiency of the all in one system: 0.8;
- capital costs per kW: 645 USD2015/kW;
- lifetime of this technology: 20 years;
- operation and maintenance cost factor (fraction of the investment cost): 1%;
- Interest rate charged on the loan for the capital cost: 5%.

Oil-fired boiler for STD 1 and STD 2 presents these features:

- efficiency of the all in one system: 0.8;
- capital costs per kW: 493 USD2015/kW;
- lifetime of this technology: 20 years;
- operation and maintenance cost factor (fraction of the investment cost): 1%;
- interest rate charged on the loan for the capital cost: 5%;

4.1.9.3 Type of electrical supply system

Portuguese consumer energy mix, for the whole district:

- efficiency of the all in one system: 0.99;
- capital costs per kW: 1 USD2015/kW;
- lifetime of this technology: 20 years;
- operation and maintenance cost factor (fraction of the investment cost): 1%;
- interest rate charged on the loan for the capital cost: 5%.

Type of cooling supply system is necessary for the district. The cooling energy is generated by the mini-splits o central A/C, private air conditioning systems.

4.1.10 Schedule

The last but not the least factor which contributes to the energy demand is the schedule. It depends on the use-type of the buildings and is organized by 9 voices: occupancy, appliances, lighting, water, heating, cooling, processes, servers, and electromobility. Each category has a schedule belonging to the use-type of buildings. Following a standard schedule built for each category. Processes, servers, and electromobility are approximated to zero hours per day since they are not influent for the buildings' use-type of VSA. Furthermore, several monthly multipliers simplify the simulation (Table 4, 5)

Table 7. School monthly multiplier

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
MONTHLY_MULTIPLIER	0.8	0.6	0.9	0.6	0.8	1	0	0.6	1	0.6	0.9	0.6

Table 8. Multi-res, food store, offices, restaurant and library monthly multiplier

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
MONTHLY_MULTIPLIER	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8

4.1.10.1 Heating schedule

The HVAC heating system contribute occurs following the setpoint hours. For each hour of the day the heating service is activated by setting "setpoint" in the respective hour box. At that point, if activated, CEA will simulate the heating power, if the room temperature goes below the setpoint temperature. Further functions are available, such as the setback, but it is not chosen for this analysis. The following schedules is applied depending on the building use-types. The hours are chosen to come from a statistic evaluation.

- School, Library: weekday 8-19 setpoint 19-8 off, Saturday and Sunday off (no heating);
- multi-residential: Saturday, Sunday and weekday 7-22 setpoint 22-7 off;
- police station: everyday 8-19 setpoint 19-8 off;
- foodstore: everyday 8-21 setpoint 21-8 off;
- restaurant: Saturday and weekday 9-15 and 19-00 setpoint 15-19, 00-9 off;
- office: weekday 8-19 setpoint, weekend off (no heating).

4.1.10.2 Occupancy

The occupancy rate is another important factor for thermal comfort, which in fact depends on the amount of people in need of heating/cooling services, at a certain time. For each hour, CEA provides standard decimal values, representing the fraction of the max amount of occupancy, pre-set with the “occupancy density” input (internal loads, 4.1.4). For most of this input values, the CEA database was taken as reliable. A little customization was made for the multi-residential schedule, increasing the occupancy fraction during the day, due to the quite high percentage of older people in the country [7].

Table 9. Multi-residential occupancy schedule

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
1	1	1	1	1	1	0.6	0.5	0.5	0.5	0.5	0.5	0.8	0.7	0.5	0.5	0.5	0.5	0.8	0.8	0.8	1	1	1
1	1	1	1	1	1	0.6	0.4	0.4	0.4	0.4	0.4	0.8	0.6	0.4	0.4	0.4	0.4	0.8	0.8	0.8	1	1	1
1	1	1	1	1	1	0.6	0.3	0.3	0.3	0.3	0.3	0.8	0.5	0.3	0.3	0.3	0.3	0.8	0.8	0.8	1	1	1

Table 10. Restaurant occupancy schedule

		4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
WEEKDAY	0	0	0	0	0	0	0.23	0.23	0.23	0.6	1	0.6	0	0	0	0	0.2	0.2	0.6	1	0.2	0.2
SATURDAY	0	0	0	0	0	0	0.23	0.23	0.23	0.6	1	0.6	0	0	0	0	0.2	0.2	0.6	1	0.2	0.2
SUNDAY	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Table 11. Office occupancy schedule

		4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
WEEKDAY	0	0	0	0	0	0.2	0.6	1	1	0.8	0.4	0.6	1	0.8	0.6	0.2	0
SATURDAY	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
SUNDAY	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Table 12. Library occupancy schedule

DAY \ HOUR	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	1
SUNDAY	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	(
SATURDAY	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	(
WEEKDAY	0	0	0	0	0	0	0	0.5	0.5	0.5	0.5	0.5	1	0.5	0.5	0.5	0.5	0.5	(

Table 13. School occupancy schedule

DAY \ HOUR	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	1
SUNDAY	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	(
SATURDAY	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	(
WEEKDAY	0	0	0	0	0	0	0	0.5	0.5	0.5	0.5	0.5	1	0.5	0.5	0.5	0.5	0.5	(

Table 14. Food store occupancy schedule

	8	9	10	11	12	13	14	15	16	17	18	19	20	2
	0	0	0	0	0	0	0	0	0	0	0	0	0	(
	0.2	0.4	0.4	0.4	0.6	0.6	0.6	0.4	0.4	0.6	1	0.6	0.4	(
	0.2	0.4	0.4	0.4	0.6	0.6	0.6	0.4	0.4	0.6	1	0.6	0.4	(

4.1.10.3 Water consumption schedule

The table of water consumption rate, chosen totally following the CEA database, affects the energy demand output. The values shown in the boxes are then calculated as fractions of "peak specific daily hot water consumption [lpd=liters per day]" and "peak specific freshwater consumption (includes cold and hot water) [lpd]" (internal loads, 4.1.4).

Table 15. Multi-res water consumption schedule

DAY \ HOUR	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
SUNDAY	0.11	0.08	0.06	0.02	0.02	0.06	0.2	0.41	0.65	0.86	0.95	1	0.86	0.74	0.58	0.51	0.29	0.55	0.72	0.78	0.4	0.37	0.34	0.19
SATURDAY	0.09	0.1	0.06	0.02	0.02	0.12	0.33	0.56	0.91	0.9	0.81	0.87	0.88	0.7	0.56	0.44	0.56	0.72	1	0.79	0.44	0.43	0.35	0.21
WEEKDAY	0.08	0.04	0.01	0.01	0.02	0.38	1	0.81	0.67	0.51	0.45	0.42	0.63	0.56	0.32	0.28	0.32	0.56	0.79	0.8	0.62	0.45	0.25	0.19

Table 16. Restaurant water consumption schedule

		4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
WEEKDAY	0	0	0	0	0	0	0.23	0.23	0.23	0.6	1	0.6	0	0	0	0	0.2	0.2	0.6	1	0.2	0.2
SATURDAY	0	0	0	0	0	0	0.23	0.23	0.23	0.6	1	0.6	0	0	0	0	0.2	0.2	0.6	1	0.2	0.2
SUNDAY	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Table 17. Police office water consumption schedule

DAY \ HOUR	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
SUNDAY	0	0	0	0	0	0	0	0.1	0.3	0.5	0.5	0.4	0.2	0.3	0.5	0.4	0.3	0.1	0	0	0	0	0	0
SATURDAY	0	0	0	0	0	0	0	0.1	0.3	0.5	0.5	0.4	0.2	0.6	0.5	0.4	0.3	0.1	0	0	0	0	0	0
WEEKDAY	0	0	0	0	0	0	0	0.2	0.6	1	1	0.8	0.4	0.6	1	0.8	0.6	0.2	0	0	0	0	0	0

Table 18. Library water consumption schedule

7	8	9	10	11	12	13	14	15	16	17	18	19
0	0.5	0.5	0.5	0.5	0.5	1	0.5	0.5	0.5	0.5	0.5	0
0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0

Table 19. School water consumption schedule

8	9	10	11	12	13	14	15	16	17	1
0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0
0.01	0.02	0.03	0.03	0.02	0.01	0.02	0.03	0.03	0.01	0

Table 20. Food store water consumption schedule

7	8	9	10	11	12	13	14	15	16	17	18	
0	0	0	0	0	0	0	0	0	0	0	0	(
0	0	0	0	0	0	0	0	0	0	0	0	(
0	0.2	0.4	0.6	0.8	0.8	0.4	0.6	0.8	0.8	0.4	0.2	(

Table 21. Office water consumption schedule

		4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
WEEKDAY	0	0	0	0	0	0.2	0.6	1	1	0.8	0.4	0.6	1	0.8	0.6	0.2
SATURDAY	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
SUNDAY	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

4.1.10.4 Cooling schedule

As the heating schedule, it works by the setpoint hours setting, following the cooling setpoint temperature pre-set. The service for the multi-res and school is totally disabled (selecting OFF for the whole day), according to the previous considerations. Only few buildings belonging to other use-type (service) are maintained active, following the CEA datasheet.

- Library: Weekday 8-19 setpoint 19-8 off, Weekend off;
- multi-residential, school: always off;
- police station: everyday 8-19 setpoint, 19-8 off;
- food store: everyday 8-21 setpoint, 21-8 off;
- restaurant: Saturday and weekday 9-15, 19-22 setpoint, 15-19, 19-9 off;
- office: weekday 8-19 setpoint, weekend off.

4.1.10.5 Lighting schedule

Even for the lighting schedule the CEA datasheets are totally kept as input.

Table 22. Multi-res lighting consumption schedule

DAY \ HOUR	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
SUNDAY	0.1	0.1	0.1	0.1	0.1	0.2	0.8	0.2	0.1	0.1	0.1	0.1	0.8	0.2	0.1	0.1	0.1	0.2	0.8	1	0.2	0.2	0.2	0.1
SATURDAY	0.1	0.1	0.1	0.1	0.1	0.2	0.8	0.2	0.1	0.1	0.1	0.1	0.8	0.2	0.1	0.1	0.1	0.2	0.8	1	0.2	0.2	0.2	0.1
WEEKDAY	0.1	0.1	0.1	0.1	0.1	0.2	0.8	0.2	0.1	0.1	0.1	0.1	0.8	0.2	0.1	0.1	0.1	0.2	0.8	1	0.2	0.2	0.2	0.1

Table 23. School lighting consumption schedule

DAY \ HOUR	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
SUNDAY	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
SATURDAY	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
WEEKDAY	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.4	0.6	0.8	1	0.8	0.2	0.6	1	0.8	0.8	0.4	0.1	0.1	0.1	0.1	0.1	0.1

Table 24. Police station lighting consumption schedule

DAY \ HOUR	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
SUNDAY	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.3	0.2	0.5	0.4	0.2	0.3	0.5	0.4	0.3	0.1	0.1	0.1	0.1	0.1	0.1	0.1
SATURDAY	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.3	0.4	0.5	0.4	0.2	0.3	0.5	0.4	0.3	0.1	0.1	0.1	0.1	0.1	0.1	0.1
WEEKDAY	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.2	0.6	0.8	1	0.8	0.4	0.6	1	0.8	0.6	0.2	0.1	0.1	0.1	0.1	0.1	0.1

Table 25. Restaurant lighting consumption schedule

DAY \ HOUR	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
SUNDAY	0.1	0.1	0.1	0.1	0.1	0.13	0.3	0.13	0.1	0.1	0.1	0.1	0.3	0.13	0.1	0.1	0.1	0.13	0.3	0.35	0.13	0.13	0.13	0.1
SATURDAY	0.1	0.1	0.1	0.1	0.1	0.13	0.3	0.13	0.32	0.32	0.32	0.46	0.94	0.77	0.1	0.1	0.1	0.13	0.51	0.57	0.49	0.77	0.63	0.32
WEEKDAY	0.1	0.1	0.1	0.1	0.1	0.13	0.3	0.13	0.32	0.32	0.32	0.46	0.94	0.77	0.1	0.1	0.1	0.13	0.51	0.57	0.49	0.77	0.63	0.32

Table 26. Library lighting consumption schedule

DAY \ HOUR	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
SUNDAY	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
SATURDAY	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
WEEKDAY	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.5	0.5	0.5	0.5	0.5	1	0.5	0.5	0.5	0.5	0.5	0.1	0.1	0.1	0.1	0.1	0.1

Table 27. Foodstore lighting consumption schedule

DAY \ HOUR	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
SUNDAY	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2
SATURDAY	0.2	0.2	0.2	0.2	0.2	0.2	0.2	1	1	1	1	1	1	1	1	1	1	1	1	1	0.2	0.2	0.2	0.2
WEEKDAY	0.2	0.2	0.2	0.2	0.2	0.2	0.2	1	1	1	1	1	1	1	1	1	1	1	1	1	0.2	0.2	0.2	0.2

Table 28. Office lighting consumption schedule

DAY \ HOUR	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
SUNDAY	0.1	0.1	0.1	0.1	0.1	0.11	0.2	0.11	0.1	0.1	0.1	0.1	0.2	0.11	0.1	0.1	0.1	0.11	0.2	0.23	0.11	0.11	0.11	0.1
SATURDAY	0.1	0.1	0.1	0.1	0.1	0.11	0.2	0.11	0.1	0.1	0.1	0.1	0.2	0.11	0.1	0.1	0.1	0.11	0.2	0.23	0.11	0.11	0.11	0.1
WEEKDAY	0.1	0.1	0.1	0.1	0.1	0.11	0.2	0.2	0.53	0.7	0.87	0.7	0.46	0.54	0.87	0.7	0.53	0.2	0.2	0.23	0.11	0.11	0.11	0.1

4.1.10.6 Appliances

Even in the case of the appliances, the CEA datasheets are totally kept as input. However, they have a quite lower weight on the energy demand.

Table 29. School appliance consumption schedule

DAY \ HOUR	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
SUNDAY	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
SATURDAY	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
WEEKDAY	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.4	0.6	0.8	1	0.8	0.2	0.6	1	0.8	0.8	0.4	0.1	0.1	0.1	0.1	0.1	0.1

Table 30. Restaurant appliance consumption schedule

DAY \ HOUR	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
SUNDAY	0.1	0.1	0.1	0.1	0.1	0.18	0.66	0.18	0.1	0.1	0.1	0.1	0.66	0.18	0.1	0.1	0.1	0.18	0.66	0.82	0.18	0.18	0.18	0.1
SATURDAY	0.1	0.1	0.1	0.1	0.1	0.18	0.66	0.18	0.16	0.16	0.16	0.2	0.84	0.36	0.1	0.1	0.1	0.18	0.72	0.88	0.28	0.36	0.32	0.16
WEEKDAY	0.1	0.1	0.1	0.1	0.1	0.18	0.66	0.18	0.16	0.16	0.16	0.2	0.84	0.36	0.1	0.1	0.1	0.18	0.72	0.88	0.28	0.36	0.32	0.16

Table 31. Police station appliance consumption schedule

DAY \ HOUR	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
SUNDAY	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.3	0.4	0.5	0.4	0.2	0.3	0.5	0.4	0.3	0.1	0.1	0.1	0.1	0.1	0.1	0.1
SATURDAY	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.3	0.4	0.5	0.4	0.2	0.3	0.5	0.4	0.3	0.1	0.1	0.1	0.1	0.1	0.1	0.1
WEEKDAY	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.2	0.6	0.8	1	0.8	0.4	0.6	1	0.8	0.6	0.2	0.1	0.1	0.1	0.1	0.1	0.1

Table 32. Multi-res appliance consumption schedule

DAY \ HOUR	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
SUNDAY	0.1	0.1	0.1	0.1	0.1	0.2	0.8	0.2	0.1	0.1	0.1	0.1	0.8	0.2	0.1	0.1	0.1	0.2	0.8	1	0.2	0.2	0.2	0.1
SATURDAY	0.1	0.1	0.1	0.1	0.1	0.2	0.8	0.2	0.1	0.1	0.1	0.1	0.8	0.2	0.1	0.1	0.1	0.2	0.8	1	0.2	0.2	0.2	0.1
WEEKDAY	0.1	0.1	0.1	0.1	0.1	0.2	0.8	0.2	0.1	0.1	0.1	0.1	0.8	0.2	0.1	0.1	0.1	0.2	0.8	1	0.2	0.2	0.2	0.1

Table 33. Library appliance consumption schedule

DAY \ HOUR	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
SUNDAY	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
SATURDAY	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
WEEKDAY	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.5	0.5	0.5	0.5	0.5	1	0.5	0.5	0.5	0.5	0.5	0.1	0.1	0.1	0.1	0.1	0.1

Table 34. Foodstore appliance consumption schedule

DAY \ HOUR	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
SUNDAY	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2
SATURDAY	0.2	0.2	0.2	0.2	0.2	0.2	0.2	1	1	1	1	1	1	1	1	1	1	1	1	1	0.2	0.2	0.2	0.2
WEEKDAY	0.2	0.2	0.2	0.2	0.2	0.2	0.2	1	1	1	1	1	1	1	1	1	1	1	1	1	0.2	0.2	0.2	0.2

Table 35. Office appliance consumption schedule

DAY \ HOUR	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
SUNDAY	0.1	0.1	0.1	0.1	0.1	0.15	0.47	0.15	0.1	0.1	0.1	0.1	0.47	0.15	0.1	0.1	0.1	0.15	0.47	0.58	0.15	0.15	0.15	0.1
SATURDAY	0.1	0.1	0.1	0.1	0.1	0.15	0.47	0.15	0.1	0.1	0.1	0.1	0.47	0.15	0.1	0.1	0.1	0.15	0.47	0.58	0.15	0.15	0.15	0.1
WEEKDAY	0.1	0.1	0.1	0.1	0.1	0.15	0.47	0.2	0.33	0.43	0.52	0.43	0.61	0.39	0.52	0.43	0.33	0.2	0.47	0.58	0.15	0.15	0.15	0.1

4.2 Current analysis

Among City Energy Analyst’s output, the main influent results for the analysis can be listed in comfort result, energy consumption (final use) and emissions.

4.2.1 Comfort chart

4.2.1.1 Adaptive comfort and Givoni diagram

The concept of *Adaptive comfort* derives from a series of statistical studies conducted in real buildings (ASHREAE). It has been observed that very often people are more tolerant than other models (Fanger) suggest. This evaluation allows to obtain comfort at much lower energy costs. The new European standard introduces this model for naturally cooled buildings, namely *passive cooling* [44].

The passive cooling can be offered in cities such as Lisbon, where the moderate wind [12] allows for effective night ventilation strategies (with which the cold air night is used to cool the thermal mass of the building).

All the CEA comfort results are shown through a Givoni type diagram, which allows to determine the bioclimatic strategy to be adopted, based on the hygrothermal conditions of the building, in a given period of the year. The comfort zone representation is built on a psychrometric diagram and it can be further divided in several characteristic areas. Each area is associated with the respective bioclimatic techniques that allow us to reach the wellness area, shown as green shape in figure 30 [45].

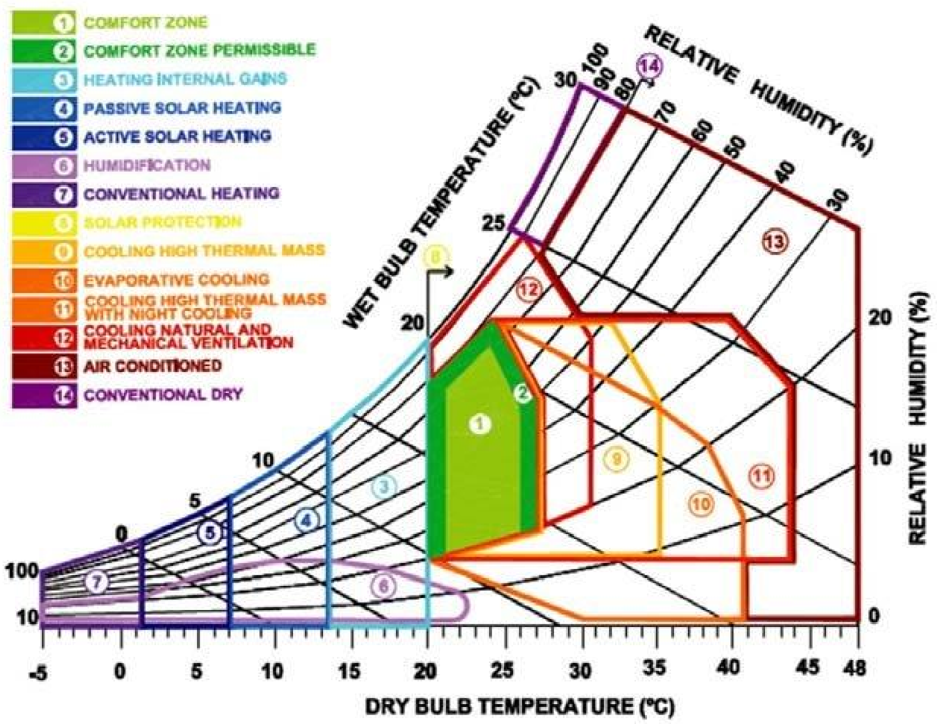


Figure 30. Givoni Bioclimatic Diagram [46]

The thermal comfort zone is defined by the dry thermometer temperature and relative humidity. By overlaying the bioclimatic Givoni diagram of the characteristic points of a particular climatic zone, resulting from the intersection between the outdoor air temperature and the specific air humidity, it has an overview of the weather conditions. According to how dense is the concentration of these points on specific areas of the graph, a certain design strategy may be applied to the building, namely cooling or heating systems.[47]

4.2.1.2 Current VSA comfort

In the CEA comfort calculation, in each plot many points are representing the single hours occupied by users in the building, (the unoccupied hours can be obscured, as in figure 13). Each building has its own chart; thus 110 different comfort plots are available as output. Among them, they were chosen one random chart for each STANDARD number: figure 25 (STD 1), 26 (STD 2), 27 (STD 4), 28 (STD 5).

Following the country's trend, the VSA current scenario shows a huge lack of thermal comfort in all the buildings. Despite the weather is quite warm of the geographic area, properly considered by the weather input, a massive heat loss determines a large area out of comfort. The age of the buildings together with the absence of a reliable heating system is determinant, especially for the high thermal transmittance of surfaces. No relevance differences are visible changing the STD, since every chart present approximately the same amount of points out of the comfort area. Other charts have been calculated and analyzed, without finding any relevant improvement.

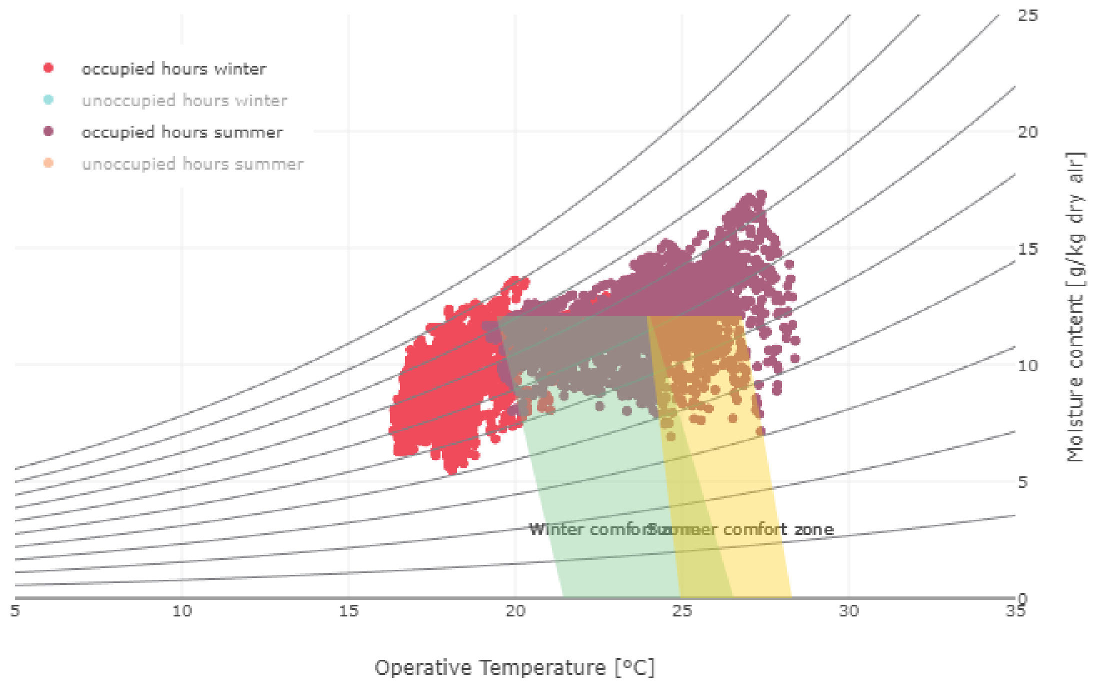


Figure 31. Building 1010 comfort chart (STD 1)

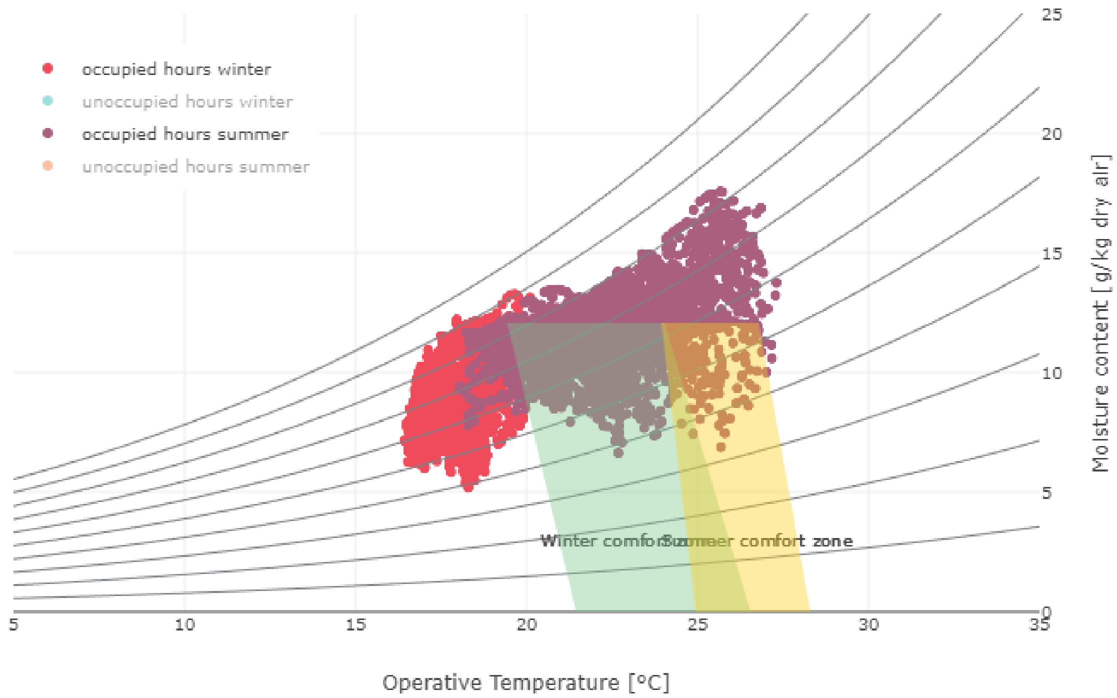


Figure 32. Building 1003 comfort chart (STD 2)

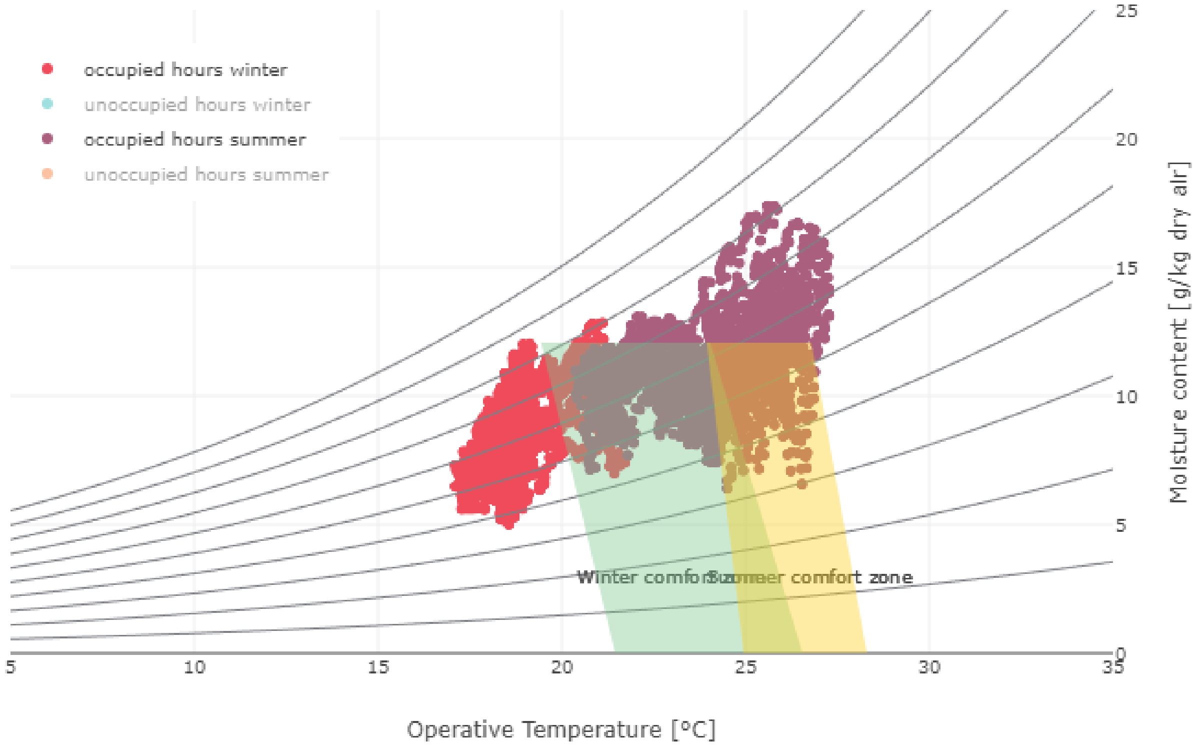


Figure 33. Building 1030 comfort chart (STD 4)

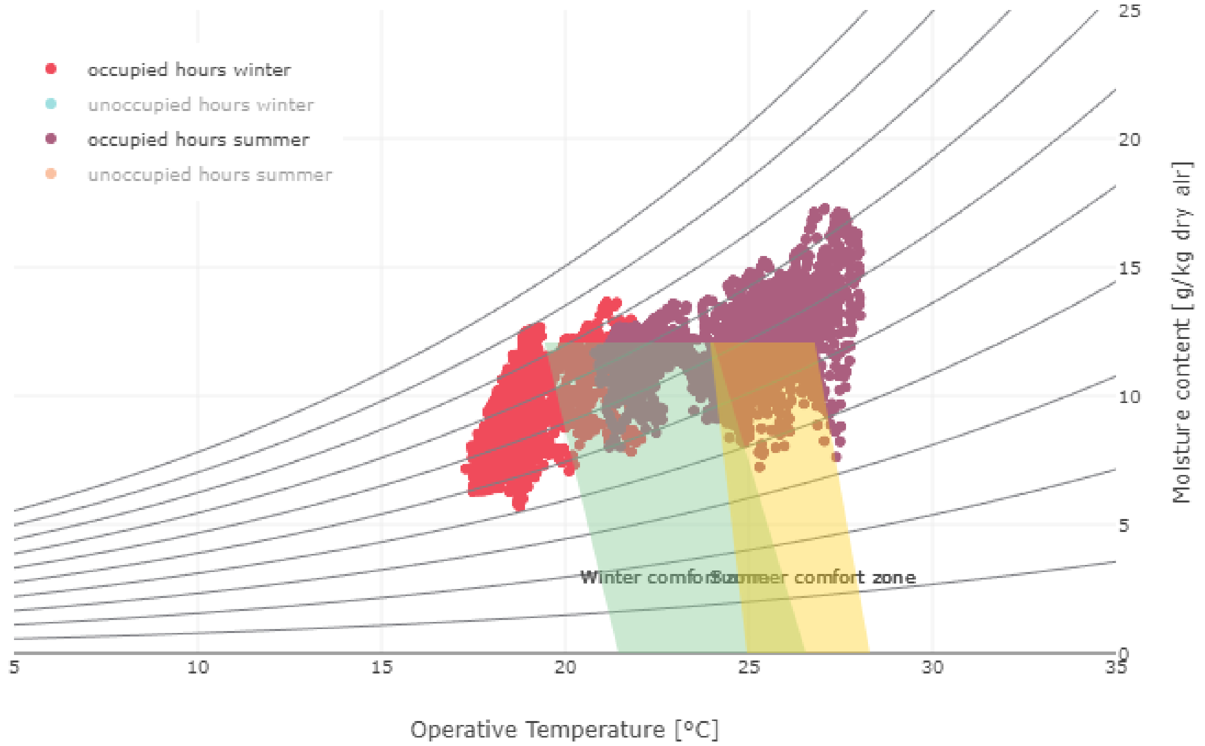


Figure 34. Building 1060 comfort chart (STD 5)

4.2.2 Energy demand

The result of a 2010 INE survey shows that total consumption in homes was 2916026 toe (equivalent to 45729,276 GWh), so in average terms, each accommodation in Portugal consumed 0,742 toes in the year of 2010. Another comparison can be done with ADENE data about Lisbon that shows the energy intensity of the buildings by the construction period, where it is visible a net decrease of energy per square meters occurs around the new millennium (figure 35) [18].

In order to figure out the CEA consumption of the VSA buildings, a large histogram presents the consumption of all buildings in the district, a graph with unevenness due mainly to the different sizes of the houses there collected (figure 36). However, to be more accurate, one building for each different STD was selected, trying to keep the surfaces as similar as possible in terms of square meters. All the STD 1 buildings are quite smaller than the unique STD 5 building (the school), so the reference area was taken around the largest STD 1 surface, 500 m^2. The result of the calculation shows that, even if the school area is much larger, the consumptions are not proportional; the latest building (STD 5) consumptions are higher, but not significantly, considering the large area gap (figure 37).

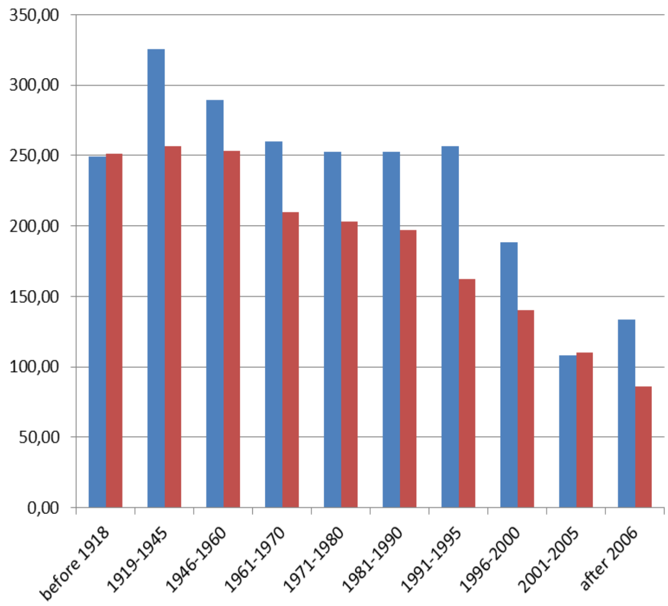


Figure 35. Average Lisbon annual energy needs for a single building [kWh/m^2 × yr] (buildings in blue, multi-family buildings in red ; ADENE)

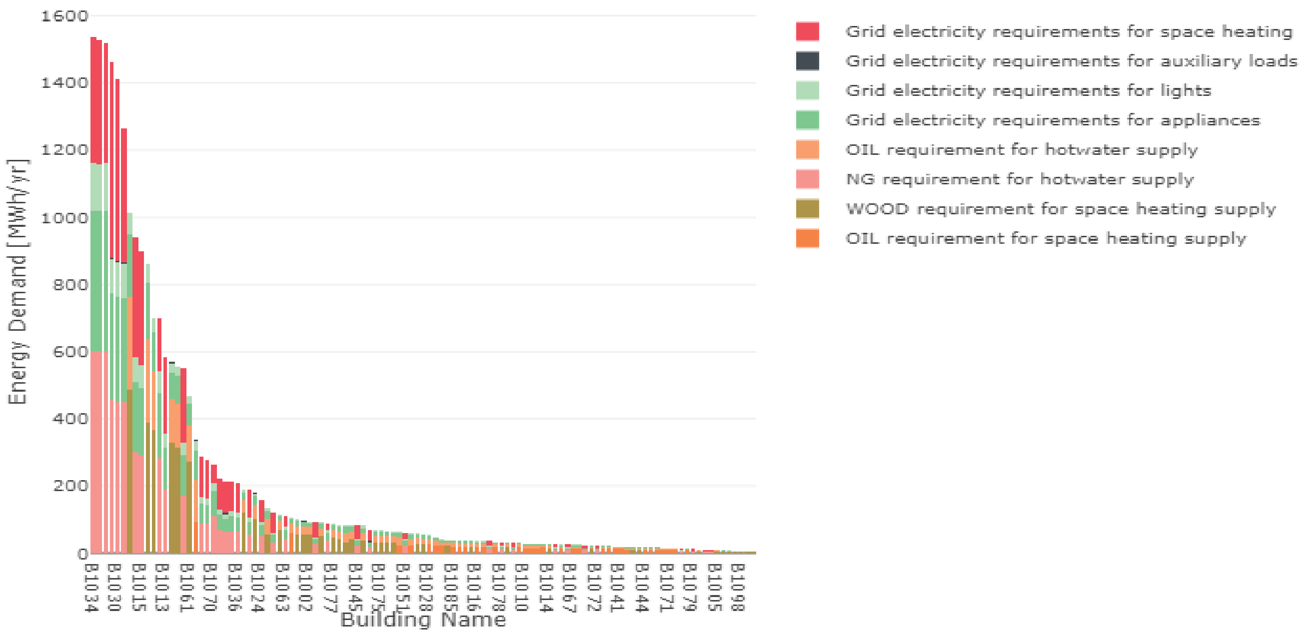


Figure 36. Energy final use [MWh\yr] for the district (CEA plot)

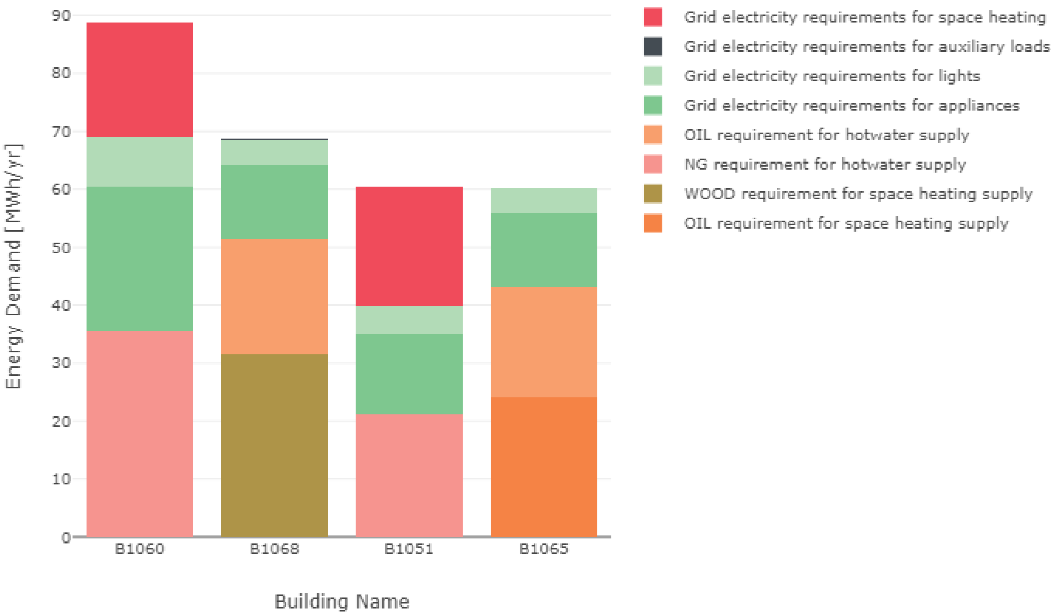


Figure 37. Energy final-use for selected buildings [MWh\yr], from left STD 5, STD 4, STD 2, STD 1 (CEA plot)

Therefore, a further plot was calculated, aiming to the Energy Use Intensity [kWh/m^2 × yr], a clearer proof of which system is more energetic expensive and obsolete. Even for this category, both ranges are shown, total and singular buildings. From the district plot occurs a clear distribution of wood and oil-based buildings next to the highest intensities. In fact, as the STD levels improve, and then they turn to carbon-free sources, the intensity decreases proportionally (figure 38).

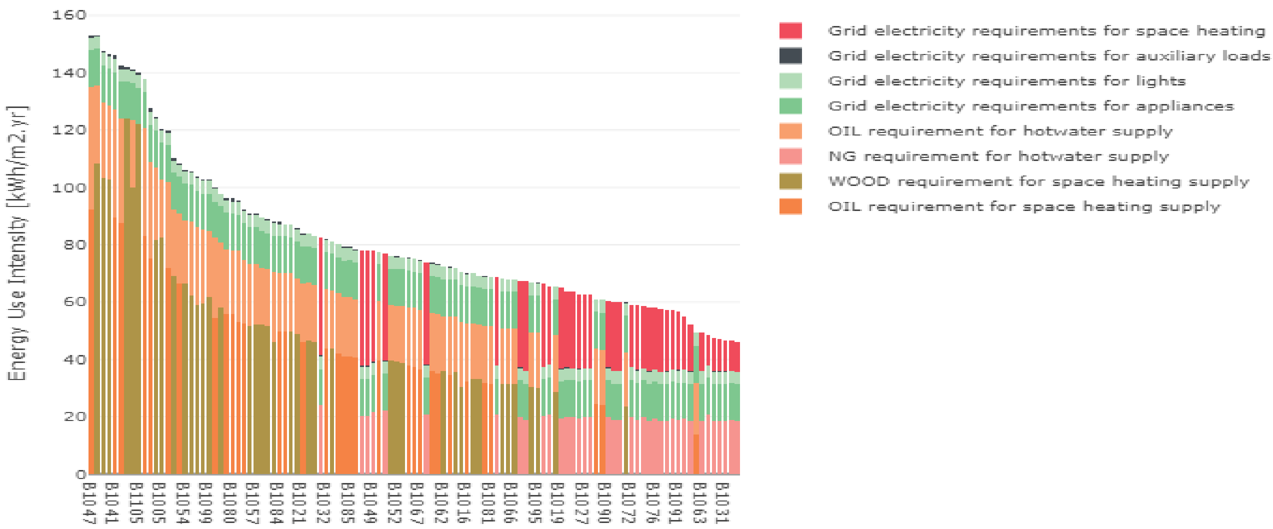


Figure 38. Energy final use intensity [MWh\yr.*m²] for the district (CEA plot)

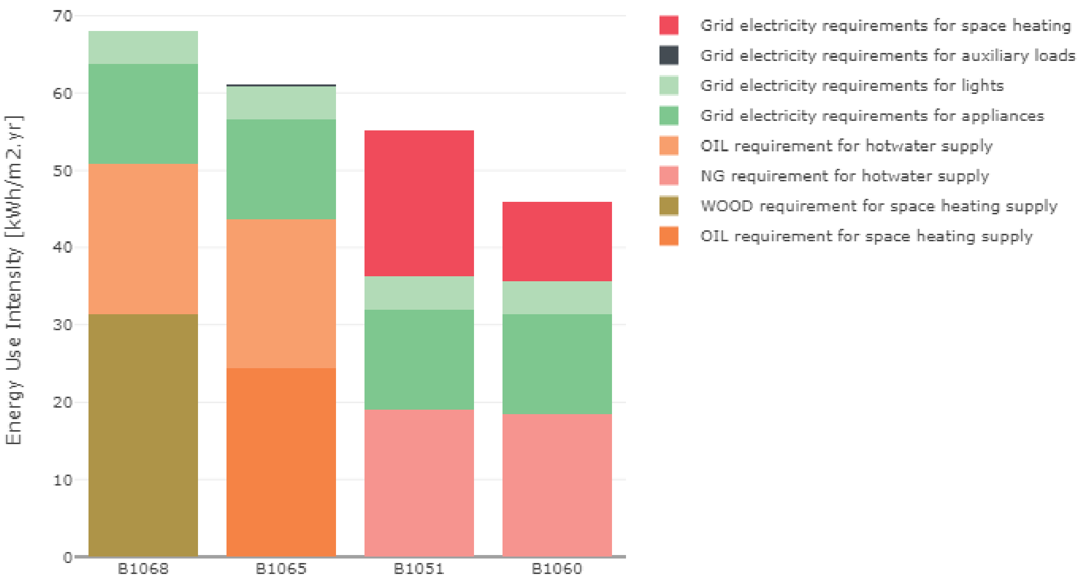


Figure 39. Energy final use intensity for selected buildings [MWh\m²*yr.] by building type, from left STD 5, STD 4, STD 2, STD 1.

Furthermore, a comparison could be made between these results and ADENE data [18]. Actually, only the energy intensity plots could be considered as comparable, since it normalizes the energy by the net floor area, so no issue due to the heterogeneous buildings' dimension occurs.

The actual data collection shows that in 2009, in Portugal, energy consumption in the domestic sector per capita was 0.30 toe. Converted in kwh, it amounts to 3,489 kwh/inhabitant. Assuming a range that goes from 20 to 40 m^2 as the average surface occupied by an inhabitant, the annual consumption could equal from 87 to 174 [kWh/m^2 × yr]. Another estimation of the consumption [kWh/m^2 × yr] could be obtained taking into account the total energy per house in Portugal (0.76 toe = 8.838 kwh) dividing by the average surface heated, according to the report (50 m^2): the resulting demand is 172.4 [kWh/m^2 × yr] [16]. However, looking at the Lisbon data in Figure 35 the energy needs are lower, especially considering the 2006 multi-residential buildings, 80 [kWh/m^2 × yr], instead of the single houses, that reach about 130 [kWh/m^2 × yr]. Furthermore, they are the closest values with CEA district demand, which goes from 50 to 150, 80 [kWh/m^2 × yr] on average (Figure 38). The data obtained though CEA are so comparable with the real VSA.

4.2.3 Emissions

According to IEA, in the past 10 years, there has been no significant emissions changes in Portugal (considering all the sectors, 48 Mt total CO2eq emission in 2010 and 47 Mt in 2018). In the 2010 INE survey is reported that 21.5% of Portugal's total emission is associated with energy consumption in housing, 2.5 million tons of CO2-eq, and 628 kg CO2-eq/house. Considering each house composed by 50 m^2, it equivales to 12.56 kg CO2-eq/m^2, that is around 0.1 kg CO2-eq/kwh considering the average consumption per meter [140 kWh/m^2 × yr][18].

Through the Life Cycle Analysis tool, CEA can evaluate the emissions (CO2-equivalent) and the result obtained is not far from the 2010 data collected. Two plots are shown, one about emission per occupancy and then the emission per square meter. With an amount of 610 kg/year × pax, the first plot gave almost the same value of the emission per house from INE (628 kg CO2-eq/house); Although for each house we should consider more than one occupant, it can be considered an acceptable result.

A further result for checking the LCA reliability might be obtained by another CEA graph, about the emissions per net area. Comparing the result (16 kg CO2-eq/m2 × yr.) with the same unit of measurement derived from INE report (12.56 kg CO2-eq/m^2 × yr) does not show a huge gap. However, seeing the same comparison from another view, multiplying for the average house dimension (50 m2/house), they give another impression, about 800 kg/y × house rather than 610.

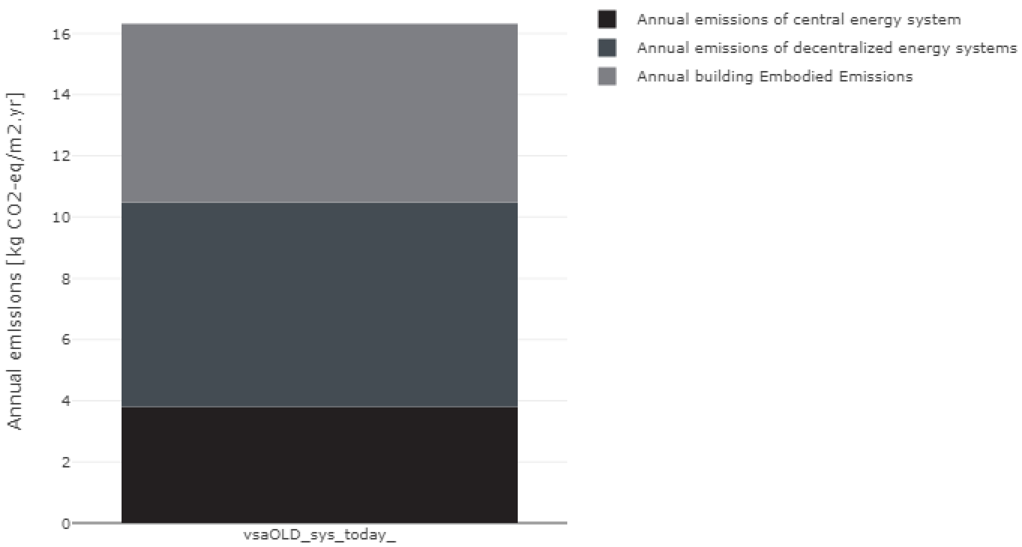


Figure 40. District annual emissions per area [kg CO2-eq/m².yr]

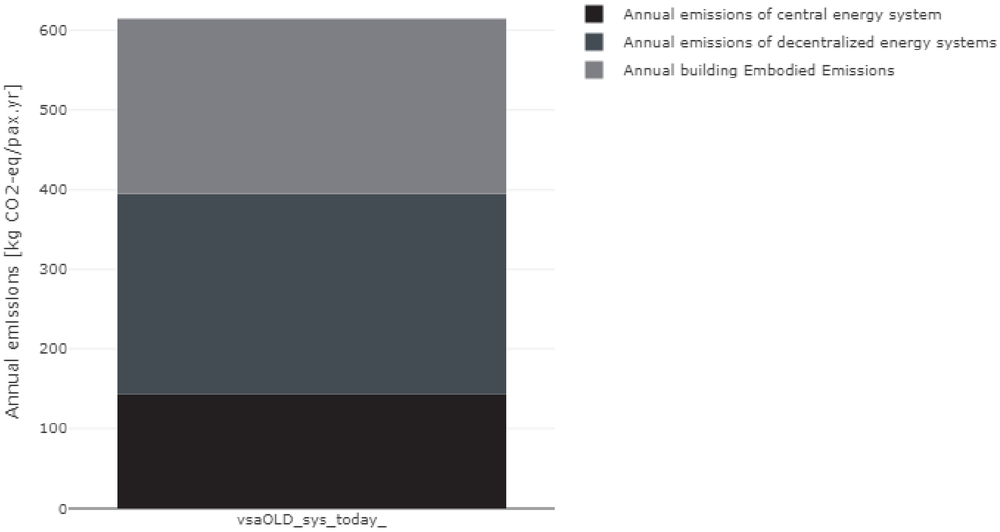


Figure 41. District annual emissions per occupancy [kg CO2-eq/pax.yr]

5 Measures - Future scenario

Following the principles for a sustainable district, the future scenario of Vale Santo Antonio is built through CEA tool. For setting the building's measures, a significative guide is conferred from European or not-government examples.

To choose the technical features, the results of many CEA calculations were compared with the database of already existing buildings in Portugal (from Aveiro and Porto districts), certified as *Passive Houses*. A Passive House is a constructive concept that defines a high-performance standard that is energy-efficient, healthy, comfortable, economically accessible, and sustainable. It is the highest standard of energy efficiency in the world: energy savings reach 75% compared to conventional buildings. It is a tried and tested solution that fully meets the definition of Nearly Zero Energy Building.

Moreover, other technical features have been provided from the European report Nearly Zero Emission Buildings (NZEB), which described many possible examples. However, no particular NZEB case is centered in Lisbon, so many comparisons with other cases City had to be studied, especially Catania, which represents the South Europe example [48][49].

This future scenario aims to maintain the same buildings, basically keeping the same existing constructions uploaded by GIS and to refurbish them. It is so necessary to upgrade the inputs for each feature already introduced for the current scenario.

Since we are not going to add any construction, the zone and the surroundings don't need any changes in the input dashboard. Regarding the envelope, HVAC and energy supply measures, more than one option will be designed.

The quantitative results obtained in this study by applying the methodology obviously depend on the assumption made about building types. It can then derive differently under several boundary conditions. Some hypotheses may not be as detailed as in the design of a specific building.

5.1 Typology

About the typology, a new STANDARD model is updated, which aims to involve all the optimizations necessary to improve the system and to reach the 2050 energy goals. This so-called STD 6 is designed in the database and is applied to the whole district through the archetypes mapper. It is initially pre-designed from a CEA Minergie's standard (Swiss specialist association) but consequently customized for the Lisbon's district needs.

The year of construction for all the buildings was maintained the same (averagely 1970) since this optimization is about a retrofitting of the original buildings. The typology of use keeps the same configuration as well (school, office, library ic.). Besides, all the internal loads and the indoor comfort setting are maintained equally.

5.2 Architecture

5.2.1 Window to wall ratio in facades facing

Generally, since the windows allow further infiltrations unless the house has a high tight, can be recommended to keep a WWR low. However, no significant changes in terms of comfort and consumptions were noted, testing combinations in the range 0.15-0.40 WWR.

The value increased year by year in the new millennium reaching 0.25 (average value among buildings and multi-family houses). Even if the Minergie STD suggests a smaller number, 0.15, for every direction (north, south, east, west), it is a feature dependent on the climate difference. So, it could be better to follow the Portuguese trend keeping higher the values. Therefore, is kept a unique value of window to wall ratio: 0.25 for north, south, east, west directions.

5.2.2 Type of construction

All the new buildings, following the STD 6 database, are converted to Heavy Constructions, therefore the internal heat capacity per unit of air-conditioned area is:

Cm_Af = 300000 [J/Km^2]

5.2.3 Tightness level.

The tightness level, the air exchanges per hour at a pressure of 50 Pa, must be higher tight. Two insulation levels are evaluated:

- “High” insulation, n50 = 0.4 [1/h] From the average value of the Portuguese Passive Houses realized;
- “Low” insulation, n50 = 0.5 [1/h] From NZEB report Catania example.

5.2.4 Roof construction type

Two main types of roofs are studied for our case study, white and green roofs. Several studies were developed about these two categories, even from the IPCC team as reported in the 2018 report [50]. Both in the CEA database are presented, then provided as two different possible solutions for VSA. Actually, the green roof seems to be the best for different reasons such as better winter insulation, longer life of the roof, pollutant filtering. However, the white roof is an inexpensive option that can keep a good level of insulation and sunbeams reflection (even higher than the green), so perhaps a choice more affordable for VSA. Further examples of Passivhaus have a U value even lower (0.148), but it is right to remember that we are considering houses in the center-north of Portugal, which has a little different climate.

- High - CEA database (white paint over plaster over concrete), U = 0.2 [W/m^{2}K]; a = 0.3; e = 0.84; r = 0.7; GHG = 113 [kg CO2-eq/m^2];
- Low - NZEB datasheet (Catania), U = 0.38 [W/m^{2}K]; r = 0.5;

- Bonus option – CEA database (Greenery roof), U = 0.15 [W/m^{2}K]; a = 0.5; e = 0.95; r = 0.5; GHG = 112 [kg CO2-eq/m^2];

5.2.5 External wall construction type

A trendy configuration of the external wall from Passive House database is a mix made by interior plaster, thermal block and EPS, with an average U value of 0.26 W/m^{2}K. However, since they are not explicated in the passive house example, the complementary coefficients necessary for the simulation come from the CEA database of the old white wall (see the current scenario). That is a possible combination given by new materials (low U-value) and the white surface that keep a high reflectance against the high solar radiance during the warm season.

- High - CEA and Passivhaus, U = 0.259 [W/m^{2}K]; r = 0.7;
- Low – NZEB Catania, U = 0.48 [W/m^{2}K]; r = 0.5;

5.2.6 Basement floor wall construction type

- High - Portuguese Passive House database, namely a mix of XPS, concrete, XPS, lightweight concrete and wood. GHG (from CEA database) = 247 [kg CO2-eq/m2]; U = 0.24 W/(m^{2}K)
- Low – NZEB Catania, U = 0.49 W/(m^{2}K)

5.2.7 Window type

Type of window inspired by the Passive House, but even present among the CEA database options. The values of the two sources are approximately the same:

- High - Triple glazing with two layers of Argon (Passivhaus and CEA), U = 0.8 W/(m2K); G = 0.5; e= 0.88; F = 0.2 GHG = 123 [kg CO2-eq/m^2].

However, there is another modern technology to consider, less usual, but more efficient:

- Low - Doble glazing with two layers of Argon (Passivhaus and CEA), U = 1.2 W/(m2K); G = 0.3; e= 0.02; F = 0.2 GHG = 123 [kg CO2-eq/m^2] (Passivhaus and CEA database).

5.3 HVAC/supply system

Among the several options illustrated in CEA Database and NZEB report, it has been chosen to focus VSA energy system on two main solutions: A Central AC (frequently involved in Passivhaus projects) and Ductless AC.

5.3.1 Cooling HVAC (emission)

As a result of climate change, South European countries like Portugal will have an average higher temperature. So, caring about the cooling system is relevant for the district, and it will be even more so in the coming decades. Whereas we are in the field of retrofit, a Mini-split system is a smart solution. Indeed, the compressor and heat exchanger can be located further away from the inside space. The whole system is quite small, so easy to install in existing homes, compared to central AC. However According to the U.S. Department of Energy, it costs up to 30 percent less to install a central air system than it does a ductless one. Nevertheless, ductless mini-splits tend to cost less to operate long-term. This is because Ductless mini-splits offer zoned temperature controls and can be also a heat source[4]. This allows you to keep rooms that you're not using warmer/cooler, which could save you money. It also means you can keep each room at a comfortable temperature for the occupant. On the other hand, the central AC offers numerous air quality products integrate easily with whole-home, ducted systems. These include humidifiers, dehumidifiers, and air purifiers. Both systems are then analyzed by CEA.

Ductless AC - Mini split datasheet (CEA Database):

- Convective part of the power of the heating system in relation to the total power: 1
- Maximum heat flow permitted by cooling system per m2 gross floor area = 150 [W/m2]
- Set-point correction for space emission systems = 0.7 [C]
- Nominal supply temperature of the water side of the air-recirculation units = 7.5 [C]
- Nominal temperature increase on the water side of the air-recirculation units = 7 [C]
- Supply air temperature of the air-recirculation units = 16 [C]

Central AC - Air diffuser (CEA Database):

- Convective part of the power of the cooling system in relation to the total power: 1
- Maximum heat flow permitted by cooling system per m2 gross floor area = 500 [W/m2]
- Set-point correction for space emission systems = 0.5 [C]
- Nominal supply temperature of the water side of the air-handling units = 7.5
- Nominal temperature increase on the water side of the air-handling units = 7
- Supply air temperature of the air-handling units = 16
- Nominal supply temperature of the water side of the air-recirculation units = 7.5 [C]
- Nominal temperature increase on the water side of the air-recirculation units = 7 [C]
- Supply air temperature of the air-recirculation units = 16 [C]

5.3.2 Cooling Supply

Ductless AC. The Heat pump air-air generates the cooling power through the indoor mini-split. Following, the general heat pump datasheet:

- Efficiency = 3
- Capital costs per kW = 700 USD/kW; (approximated from ENAT,PT source (€1700/2.5Kw)][51]
- Lifetime = 20 year
- Operation and maintenance cost factor (fraction of the investment cost) = 1
- IR = 5%

[4] Due to a CEA database lack is not allowed to set Mini-split also for the heating system

Central AC. The Heat pump air-air is selected from CEA database. Obviously, this supply requires larger dimensions than the first option and a ducts system (same heat pump general datasheet). Moreover, the cost must be split in three (cooling, heating and HW), since it is a hybrid system.

- Efficiency = 3
- Capital costs per kW = 250 USD/kW; [approximated from POSEUR, PT source (€3750/5Kw/3)] [52]
- Lifetime = 20 year;
- Operation and maintenance cost factor (fraction of the investment cost) = 1
- IR = 5%

5.3.3 Heating HVAC

Ductless - Since Minisplit is not supported as heating system from CEA, is selected the Radiator (90/70). It can take electrical power directly from the photovoltaic-thermal panels. However, the simulation is not predicting if the energy required will be satisfied totally by the solar resource, therefore the plots is not showing only "solar energy" required for the heating needs (the radiator datasheet are the same of the current scenario):

- Convective part of the power of the heating system in relation to the total power: 1
- Maximum heat flow permitted by cooling system per m2 gross floor area = 500 [W/m2]
- Nominal supply temperature of the water side of the sensible heating units = 90 [C]
- Nominal temperature increase on the water side of the sensible heating units= 20 [C]

Central AC - Air diffuser (CEA Database):

- Convective part of the power of the heating system in relation to the total power: 1
- Maximum heat flow permitted by heating system per m2 gross floor area = 500 [W/m2]
- Correction temperature of emission losses due to type of heating system = -1.1 [C]
- Nominal supply temperature of the water side of the air-handling units = 40 [C]
- Nominal temperature increase on the water side of the air-handling units = 20 [C]
- Supply air temperature of the air-handling units= 36 [C]
- Nominal supply temperature of the water side of the air-recirculation units= 40 [C]
- Nominal temperature increase on the water side of the air-recirculation units = 20 [C]
- Supply air temperature of the air-recirculation units = 36 [C]

5.3.4 Heating supply (generation)

Central AC - The heating supply is an air/air Heat pump (same pump of the cooling system), powered by Photovoltaic-thermal Panels, properly implemented by CEA "Energy potentials" tool. All the Portuguese Passive Houses examples confirm this technology as successful, in terms of self-sufficiency. General features provided by the CEA database; efficiency consistent with NZEB and Passivhaus datasheet.

- Efficiency = 2.8;
- Capital costs per kW = 250 USD/kW [approximated from POSEUR, PT source (€3750/5Kw/3)];
- Lifetime = 20 year;

- Operation and maintenance cost factor (fraction of the investment cost) = 1
- IR = 5%

Ductless AC – An alternative system from the first solution is not competitive in terms of efficiency. However, omitting that the heat by the mini-split would be enough as far the air-conditioned area is modest, further solutions are still suitable. So, as the heating supply is set an electrical boiler 100% efficient. It is a "trick" to lead the radiator to be the own electrical generator, as a simple domestic device.

- Feed: Solar energy
- Efficiency of the system = 1; (average value from web sources)
- Capital costs per kW: 1 USD2015/kW
- Lifetime of this technology: 20 years
- Operation and maintenance cost factor (fraction of the investment cost): 1%
- Interest rate charged on the loan for the capital cost: 5%

5.3.5 Control system

No type of heating and cooling control systems was applied for the old scenario, due to the systems obsolete. In an optimized scenario, the heating and cooling can count on a control system, a PI controller with optimum tuning.

- Correction temperature of emission losses due to control system of heating = 0.9 [C]
- Correction temperature of emission losses due to control system of cooling = -0.9 [C]

As opposed to a system without a controller which can lose about 2.5 [C].

5.3.6 Hot water supply

The water emission system still reaches typically 60 °C, what we are going to change is the water heating supply. Several solutions are presented for the ductless, while for the Central AC only one is relevant.

Central AC – Same complex Heat pump air-air which powers heating/cooling AC, also provides hot water. All of the energy need is powered by the thermal solar panels.

- Efficiency = 2.8
- Capital costs per kW = 250 USD/kW [approximated from POSEUR, PT source (€3750/5Kw/3)];
- Lifetime = 20 year;
- Operation and maintenance cost factor (fraction of the investment cost) = 1
- IR = 5%

Ductless AC (1) – Heat pump water/water supply system (CEA database) which is powered by the Photovoltaic-thermal Panels.

- Feed: Solar energy
- Efficiency = 3
- Capital costs per kW = 1200 USD/kW [approximated from Kuantokusta.pt] ;

- Lifetime = 20 year;
- Operation and maintenance cost factor (fraction of the investment cost) = 1
- IR = 5%

Ductless AC (2) – Electrical Boiler, which works in synergy with the Photovoltaic-thermal Panels. The software simulated to apply panels all over the district roofs. Datasheet of the system:

- Feed: Solar energy
- Efficiency of the system = 0.85; (average value from web sources)
- Capital costs per kW: 10 USD2015/kW
- Lifetime of this technology: 20 years
- Operation and maintenance cost factor (fraction of the investment cost): 1%
- Interest rate charged on the loan for the capital cost: 5%

5.3.7 Ventilation

Ductless AC – natural ventilation (night flush on).

The city's weather file is significant for ventilation since the city is normally quite windy. Therefore, a unique solution without mechanical ventilation is proposed, since it is often not required, thanks to the average high velocity of the wind (figure 42). However, the unevenness of the district could lead to comfort issues, since few areas could be particularly covered by windy flows. So, obviously, for new contractions, should be opportune to design the district ventilation needs with accuracy for each building, caring about the area morphology.

Central AC – Mechanical ventilation with demand control and economizer (night flush on, heat recovery on).

An artificial typology was chosen to combine it with the central AC configuration because of the duct system, which allows for better performance.

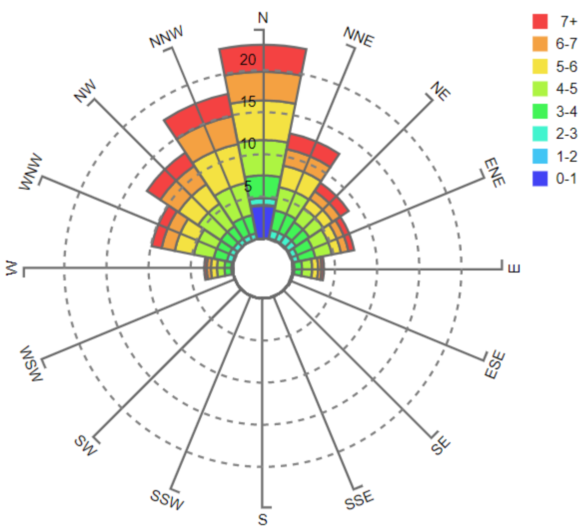


Figure 42. Frequency of wind directions and velocities [m/s] for the whole year in Lisbon (Climaplusbeta)[12]

5.4 Solutions

Considering the different options evaluated, the following retrofit strategies have been chosen for each type of building: a general increase of the insulation, which could involve two levels of intensity, accompanied by the installation of devices which provide heating, cooling and hot water heating services. Every system consumes electricity or solar energy, rather than fossil fuels. A photovoltaic-thermal panel system allows to power each building in the district, making a big contribution to energy supply. By analyzing the different alternatives, they can be synthesized in 5 combined configurations:

- Solution A: lower insulation with a central AC:
- Solution B: higher insulation with central AC;
- Solution C: higher insulation with ductless AC;
- Solution D1: lower insulation with ductless AC, hot-water by electrical boiler;
- Solution D2: lower insulation with ductless AC, hot-water by heat-pump;

The insulation involves many reinforcement on the thermal transmittance, through the application of high-performance materials on every element of the building. The two levels differ from the type of material used, so from the U-value (thermal transmittance) resulting.

Regarding the energy services, two main solutions are designed for the heating/cooling system. First, the hybrid air/air heat pump, which provides, through a centralized duct system, both heating and cooling power to the whole building. Secondly, the ductless system is powered by a mini split air-conditioner, as air cooler, along with electric radiators for the heating (unlike the duct system, this solution requires one device for each room).

Finally, for the hot water heating, three different possibility are proposed; one involves the centralized heat pump, since the hybrid configuration is also designed for the HW. The ductless system has two possibility: an electric boiler or a water source heat pump.

5.5 Results

A panoramic view of the optimized district is shown, focusing on thermal comfort, energy consumption, and emissions. The main results have been compared with the 2050 Portuguese strategy, so following the European NZEB ambitions, aiming to achieve the self-efficiency goal. For these analyses, comfort conditions, energy consumption, and emissions were compared, taking account of the economic impact.

5.5.1 Comfort chart

The next plots show the comfort chart of one random selected building, for comparing how each solution is effective. For each new configuration, the thermal comfort plot shows great improvements compared to the current scenario, being most of the occupancy points shifted toward the thermal comfort area. The ductless solutions have gained a good growth of comfort, although humidity is a little too high for both seasons. In addition, in C and D solutions, the insulation level don’t affect so much the point distribution (fig 45-46)

The most effective comfort solutions are the central AC, the A and B, whose graph shows far fewer external points from the comfort zone (fig 43-44). This could be related to the system effectiveness, but alto to the air-quality control obtained by the ducted system, which includes efficient humidifiers and dehumidifiers. Moreover, we can realize that, with a central AC, could be superfluous to have so high insulation; summer occupancy points are in good thermal condition anyway. Another significantly difference between A and B is notable in winter season, when the temperature are at least 1-2 C° less and the moisture 2-3 [g/kg dry air] more. So, generally, the higher insulation (B and C) present better conditions for the moisture level. Nevertheless, a moderate level of insulation refurbishing, case A, offers a great comfort solution, avoiding not-necessary energy consumptions and cost.

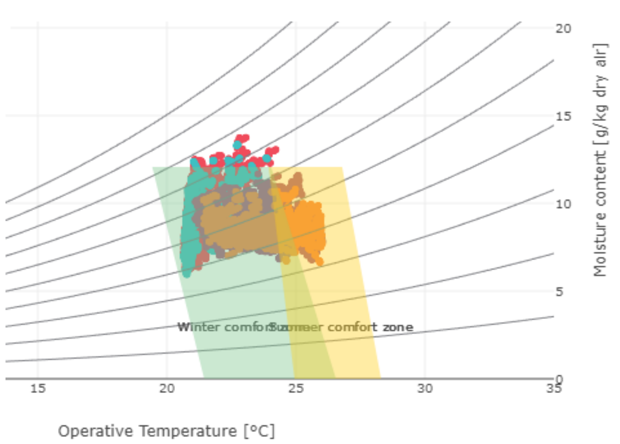


Figure 43. Comfort chart – (A) low insulation central AC

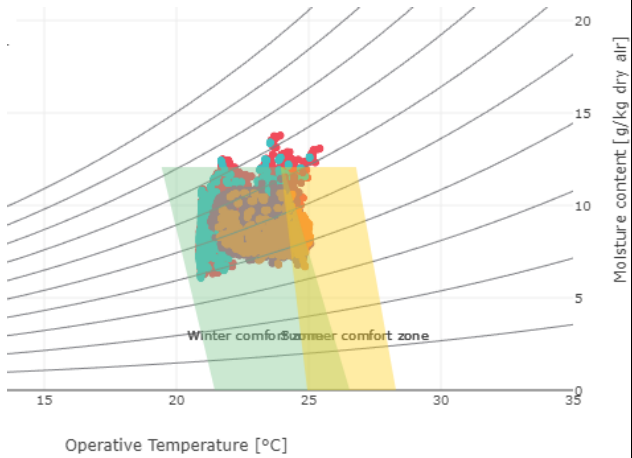


Figure 44. Comfort chart – (B) high insulation central AC

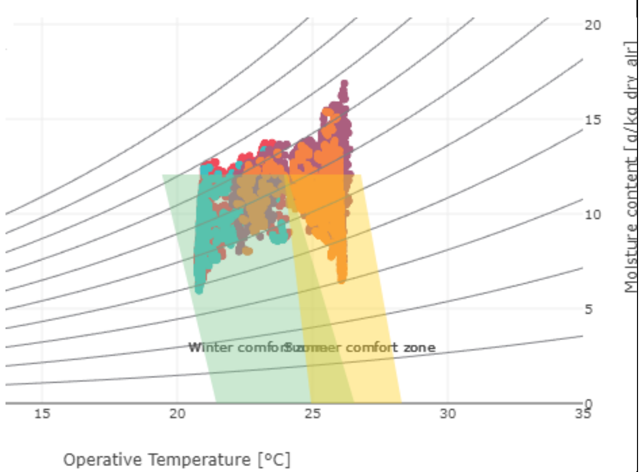


Figure 45. Comfort chart – (C) high insulation ductless AC

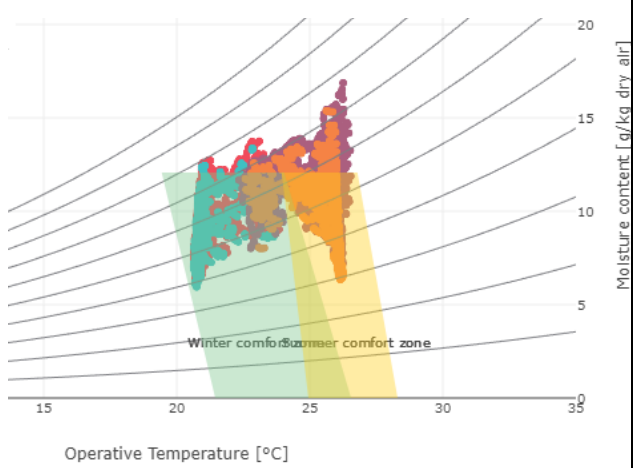
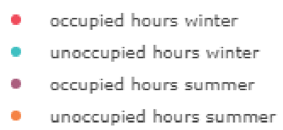


Figure 46. Comfort chart – (D1,D2) low insulation ductless AC



5.5.2 Energy – final use

Among the several outputs available, the energy demand calculation was focused on the final use, following the current scenario analysis. Compared to the old VSA, the optimization provided by the measures shows an ambitious energy transition to carbon-free supply, through to the solar energy and massive electrification of the district, cutting significantly the emissions. Furthermore, the high level of tightness carried by retrofitting, together with higher efficiency HVAC, cut significantly the consumptions.

Compared to the current VSA which measures on average 80 kWh/m^2 per year, the new VSA shows a sharp decrease of the final use, with a range which goes from the 45% of the worst scenario (D),(40 $kWh/m^2 \times yr$), to the 70% of the best one B, (25 $kWh/m^2 \times yr$).

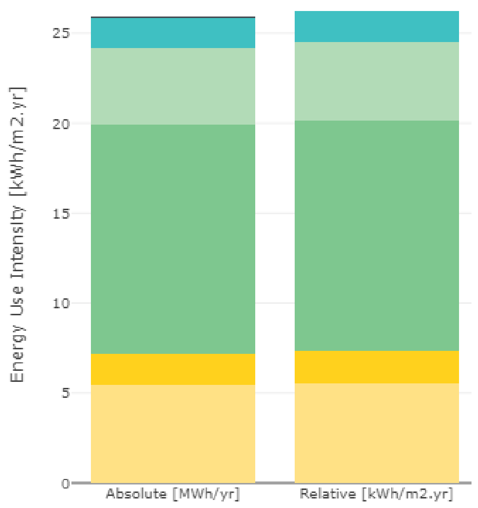


Figure 47. Energy Final Use Intensity for one Building – (A)

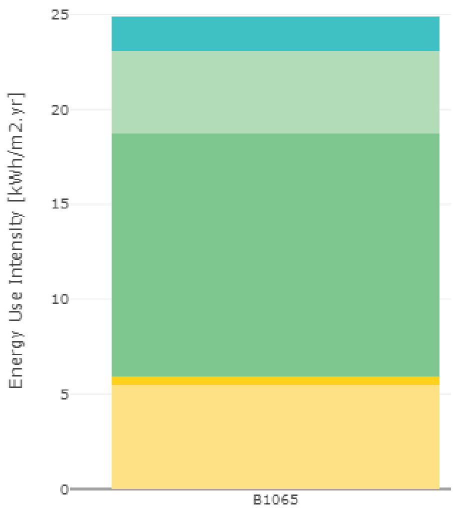


Figure 48. Energy Final Use Intensity for one Building – (B)

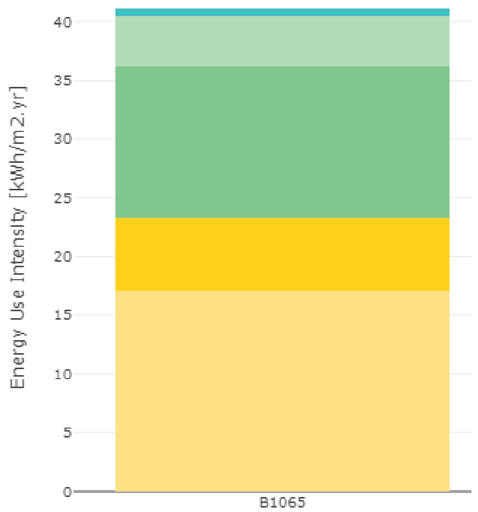


Figure 49. Energy Final Use Intensity for one Building – (C)

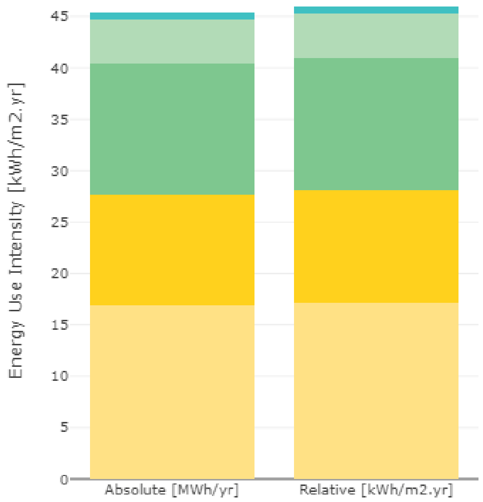


Figure 50. Energy Final Use Intensity for one Building– (D1)

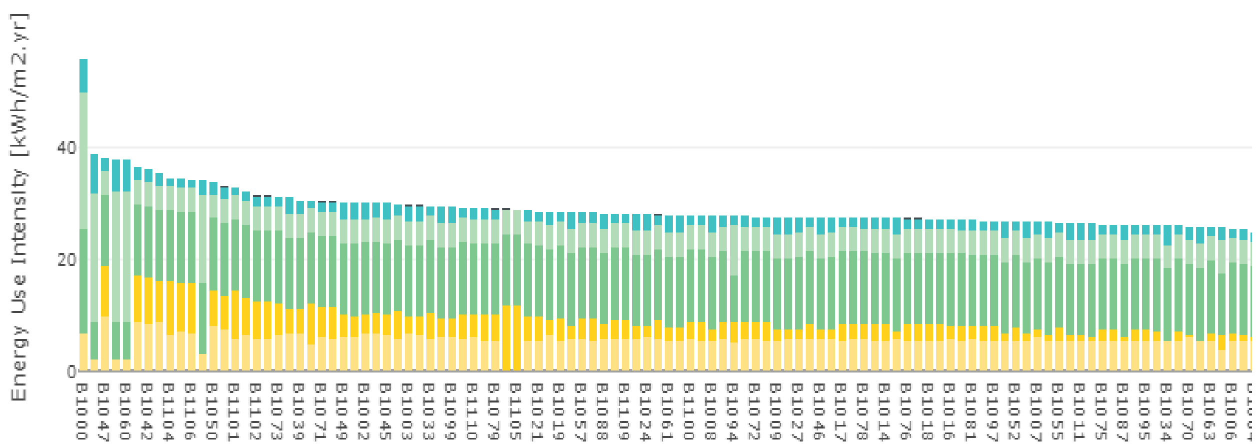


Figure 51. VSA Energy Final Use Intensity – (B)

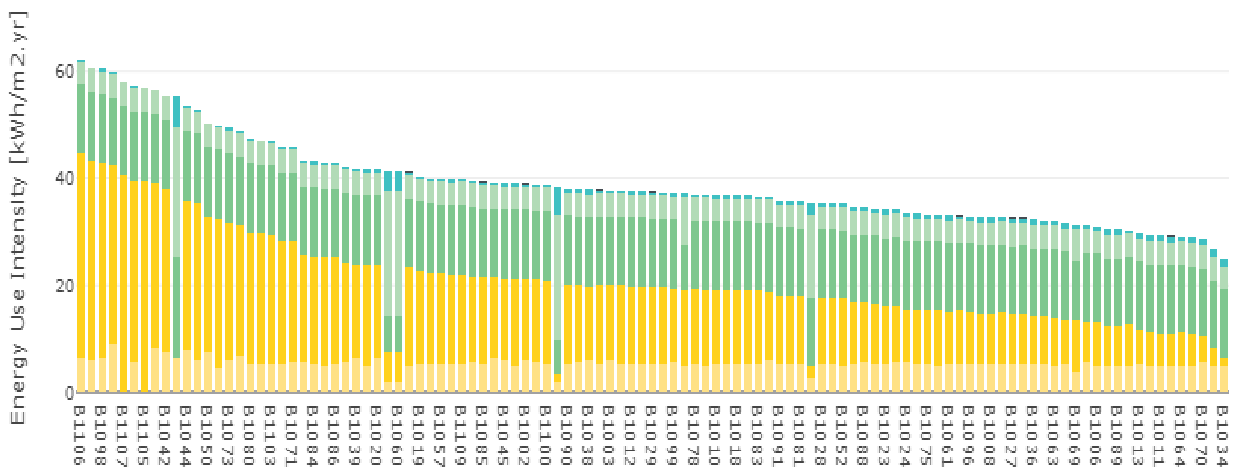


Figure 52. VSA Energy Final Use Intensity – (D2)

The central AC package, thanks to the multi-supply of the heat pump system, shows the lowest consumption. The heat-pump high efficiency allows us to feed all the utilities with about 25 kWh/m^2 × yr (B), a little more if the insulation decreases (A). Especially, with higher insulation values, heating needs are less, while cooling increases a little more. The same situation happens with a ductless configuration (C, D). Therefore, the increase in the total demand is due to the net increase in heating energy. The ductless consumptions are quite higher if we see the case C and D1, due to the heating and hot water system. The electrical radiator, although it has a low purchase price and it has rapidity in bringing heat, is much less efficient. Same for the HW system, which consumptions are three times more (from 5 to 15 kWh/ m^2 × yr.

However, the cooling demand is much smaller with the mini-split, 0,43 kWh/m^2 × yr (C) rather than 1,64 kWh/m^2 × yr (B). This plot confirms how mini-split could be a more efficient device in long-terms, at least for cooling. [53] In addition, we see another interesting scenario in D2, which mix a very efficient water/water heat pump for hot water with a mini-split, keeping the consumptions around 30 kWh/m^2 × yr.

5.5.3 Emissions

The tool LCA calculated for every solution an amount of emissions definitely lower than the current scenario – a decrease from 600 kgCO_2eq/occ × yr to 200 kgCO_2eq/occ on average. Looking at the figure 53 we see an average value of 10 kgCO_2eq/m^2 × yr, 40% less than the current scenario (16 kgCO_2eq/m^2 × yr).It is a quite good result compared to the European average level, which was around 27 kgCO_2eq/m^2 × yr in 2008 [54].

Further researches on the average emissions for one building [55] evidence almost the same value (10 kgCO_2eq/m^2 × yr) for a typical low-consumption house, but lower emissions for a self-efficiency house which should produce just 3 kgCO_2eq/m^2 × yr. The results are thus a significant cut but not enough for reaching the net zero target by 2050. However, in CEA, some inaccuracy occurs in this field; for instance, how could be the grid electricity meant by CEA, which may involve an excess of emissions per kWh produced. In fact, being the case placed in Portugal, at least 50% of the grid electricity is provided through renewable sources generation, which involves almost zero emissions.

Among the solutions, a small difference occurs for the embodied emissions (related to the physical elements of the construction), which are higher for the packages with a higher insulation. However, less insulation confirms a higher heating demand, so more emissions related to the energy system. The lowest emissions scenario possible happens when the insulation is moderately high and the supply system is very efficient, namely solution A. Higher insulations, allows to reach few degrees more during the winter but, on the other hand, they bring the CO2-eq embodied emission to an increase.

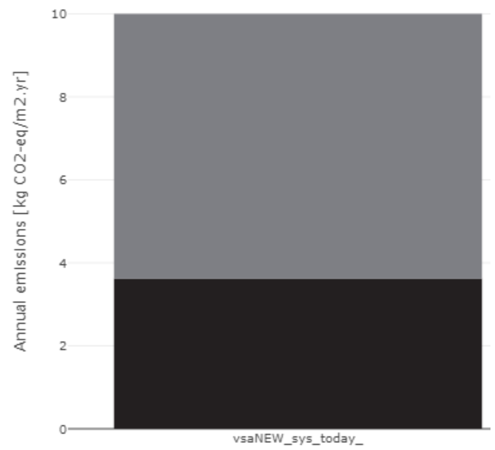


Figure 53. Annual Emissions for VSA normalized to net floor area - (A)

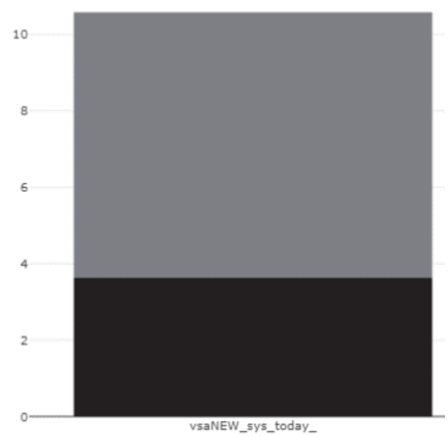


Figure 54. Annual Emissions for VSA normalized to net floor area - (B)

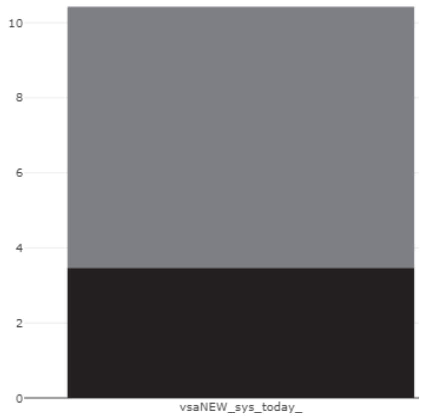


Figure 55. Annual Emissions for VSA normalized to net floor area - (C)

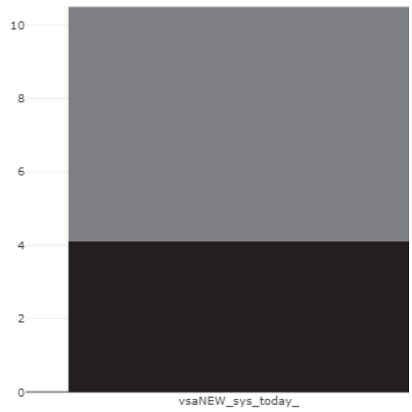


Figure 56. Annual Emissions for VSA normalized to net floor area - (D1)

Figure 57. Annual Emissions for VSA normalized to net floor area - (D2)

5.5.4 Costs

The Capex (Capital expenditures) difference between the centralized (A,B) and decentralized (C, D) air condition system generally could be various and often they are equivalent since it is a sector continuous updating and several commercially solutions are available. As stated by the U.S. Department of Energy, the installation of a mini-split system (C, D options) costs up to 30 percent more than the central air system (A, B options)[53]. Moreover, a centralized heat pump, if it is hybrid, is able to provide all the thermal energy required for heating cooling, HW and only one unit is enough to feed the entire building, saving further plants cost. Nevertheless, other sources state that installing ductwork in existing building is disruptive, time consuming and they are much more expensive than installing a ductless system, which requires just a small hole in the wall [56].

Also, according to many sources [53][56], the ductless mini-splits higher efficiency let the Opex (operating expenditure) to keep lower during the subsequent years. This evaluation comes from the fact that a ductless heat pumps can easily be customized to create the optimum temperature settings for each room. However, in the simulation this aspect is not properly faced since air-conditioned surfaces are not subjected to any customize thermal comfort, which is kept constant.

The HW cost, in the other hand, has a significant difference given by the electric boiler (C, D1) instead of the heat-pump system (A, B, D2). Although they are both fed by the Sun, the heating efficiency of electric water heater is less than 100%, while the heat pump water heater can reach 400% when the ambient temperature is high enough. Even under 0℃ ambient temperature, the heating efficiency can be 200%, far higher than the heating efficiency of electric water heater.[57] Thus, heat pump HW heating (case A, B, D2) can save more electricity and energy than electric water heater (case C, D1). In the OpEx field (OPerating Expense) this means a huge annual cost saving. On the other hand, building a HW heat pump plant could be more expensive in them of Capex, while a simple electrical boiler as an initial cost significantly lower. However, not so many input allowed to carry out an accurate evaluation of the Capex. Only the Capex (USD/Kw/year) of the energy system could be uploaded, therefore the cost difference obtained from the solutions is probably given mostly from the efficiency and the heat flow comparation among the energy system. According to the plots, the weight of the Capex is significantly irrelevant compared to the Opex. Therefore, the solution A, B, D2 present a lower amount of costs, probably mainly thanks to the lower Opex obtained by the central heat pump hybrid system.

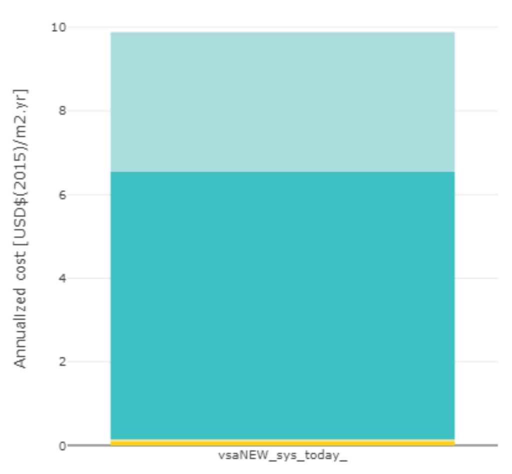


Figure 1. Annual Costs for VSA normalized to gross floor area (A)

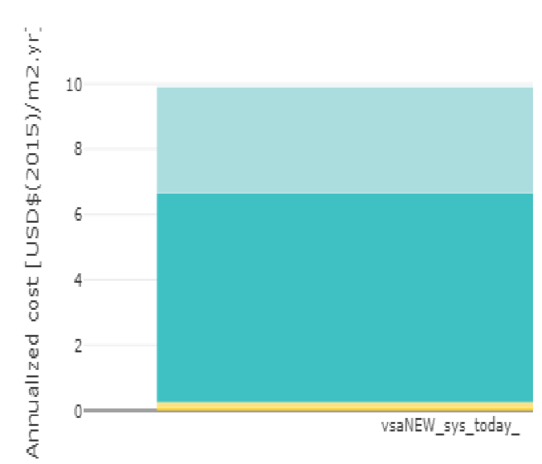


Figure 2. Annual Costs for VSA normalized to gross floor area (B)

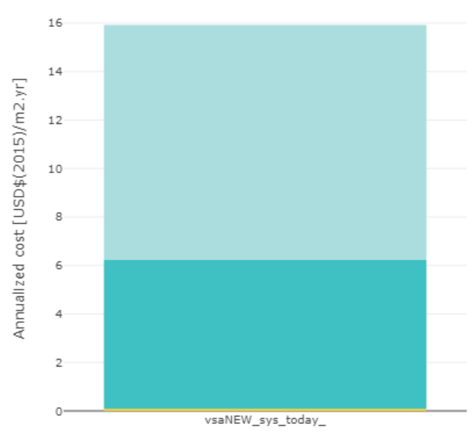


Figure 3. Annual Costs for VSA normalized to gross floor area (C)

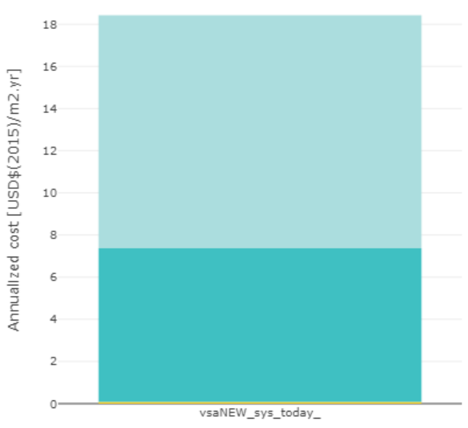


Figure 4. Annual Costs for VSA normalized to gross floor area (D1)

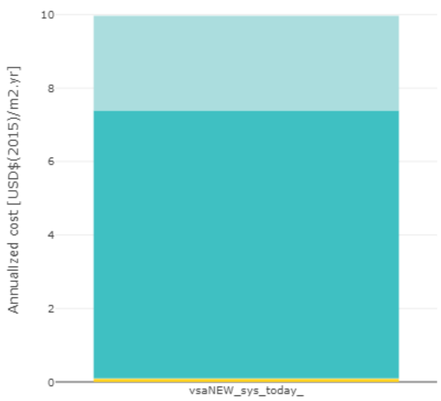
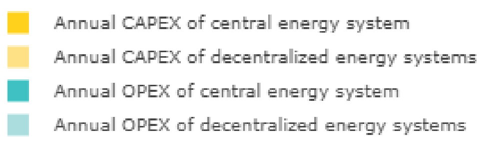


Figure 5. Annual Costs for VSA normalized to gross floor area (D2)



6 Discussion of results

6.1 Solutions evaluation

Both cases of insulation are successful in terms of comfort and in energy saving. Higher is the level of insulation set (mostly thanks to a lower transmittance, U), lower are the consumptions. Even though the CO2 emissions are slightly higher with the applications of more complex materials, a higher insulation (B, C) allows many benefits. The results may represent an interesting examples of how tackling the houses transmittance could be the key for finally fix the Portuguese comfort issue. The insulation reinforcement allows to keep the heating almost to zero, as the mild climate let us expect. So, considering these outputs as reliable, the nearly zero goal is obtained.

Looking the average district amount of the consumptions (fig. 51), it reveals a significant improvement compared to the current VSA, with a reduction from 40% (D1) to 70% (B) of kWh/m^2 × yr. Moreover, with a right amount of solar radiation most of these consumptions are absorbed from the bills. In fact, in yellow, is shown as the solar gains cover a huge percentage of the total energy final use. The remainder of the histogram is basically composed by appliance and light electricity requirement, that we can further reduce thanks to the latest smart devices and a total usage of LED technology. For reaching the highest energy saving, the central energy system is the best solution, which supported with the highest insulation almost leads to zero the heating and hot water needs. Even the comfort is totally centred in the wellness area.

Some drawbacks, however, emerge taking account the retrofit operation, such as: the intrusiveness of a duct system and its relevant investment costs. Even if the analysis result is not properly highlighting this aspect, the actual amount of Capex embodies this retrofit is strategy biggest problem. Without any investment's help these measures could be rejected, although the such proved benefits. Moreover, at the retrofit level, the footprint of a central plant could be not supported by most of the user, compared to a small gas condensing boiler, cheaper and less intrusive.

Nevertheless, a good compromise is proposed with the mini-split solution, which keep an acceptable level of comfort and consumptions, cutting up to 60% the consumption with the heat water heating heat pump, and 50% without the heat pump, but with the highest level of insulation. Probably, a better result could be obtained allowing to use the minis-pit as well as for the heating, since the electrical radiators sin of a low efficiency. This is globally a better solution terms of costs and intrusiveness, maybe more affordable for the Lisbon average customers.

Although the CEA simulation is not totally representative, it confirms which measures may represent the path to take for not depending on the fossil fuel anymore, using renewable source for cutting as more as possible the CO2 emission and for decreasing massively the OpEx costs.

6.2 Evaluations on the CEA tool

The analysis has demonstrated how the CEA choice could be right since it includes many skills when it is analyzing neighborhoods, with a much larger range of outputs than is needed. In fact, the CEA ability to better model a neighbourhood could be even deeper exploited for a district scale objective; for instance, providing the design of a district renewable source (PV panels group, wind turbines, heat ground source etc.) or the application of a local energy-thermal storage, of which only the district buildings can benefit.

It is necessary to make it clear, however, that, although it is a more than an adequate tool for this work, other tools such as UMI and CityBES could have demonstrated equal effectiveness. There would probably have been different interesting results. A future study could just go deeper and compare the various performances for the same scenario, in order to establish the actual limits and strengths of CEA on Vale Santo Antonio.

The tool represent a smart way to operate, since it provides many information simplified, which otherwise needs a lot amount of calculations. Among the several stakeholders, the function of the urban planner seems to be the most involved, for a first approach to the urban energy planning. The actual work needs, however, an inevitably next engineering work, which CEA cannot replace, but rather support in the first phase.

7 Conclusions

Portugal's long-term strategy aims to reach by 2050 the reduction of more than 95% of GHG emissions by compared to 2005; nowadays the reduction is still around -11%. Therefore, although Portugal is already well advanced in the carbon-free path established by the EU, the future energy scenario forecasts the need to have a much better evolution. It is necessary to figure out that a huge part of this step starts from the buildings (residential and service) sector.

Several tools are already facing the process, helping urban energy planners to lead the scenario towards total sustainability. Among the tools analyzed, physic-based, there are already widely used ones, such as CityBES, UMI, and CEA. They already demonstrated a useful and concrete function in the USA, Zurich, and Singapore. Other tools, on the other hand, are in development and need more experimentations to be reliably used in the UBEM trend. However, each tool can be more specialized and useful than another, according to the use needed.

CEA, meeting the expectations of the literature, demonstrated to be a suitable tool for planning at the district scale. The current VSA scenario was designed trying to be as real as possible, in order to provide a reliable starting point for the measures. According to the preliminary result of the current VSA, the tool allows following this path. The best performance of the tool needs, however, a great amount of data, which not always have been available. Despite using the data available (from ADENE, INE), many inputs had to be approximated. Some of the inputs derived from the CEA database, only partially suitable since it is initially designed for Zurich and Singapore environments. The results are so, not extremely reliable due to such causes of inaccuracy. However, they show a good level of coherence, comparing the VSA plots with the actual Portuguese energy demand and emissions.

Several tests have been done, but only a few of the several solutions possible were implemented. The final result had a wide differentiation due to the unevenness of the boundary conditions among the district. Indeed, going to a smaller scale, some buildings could adopt a more customized system, choosing the optimal heating/cooling schedule, and the right insulation package, in order to have the perfect comfort/consumption conditions. However, proceeding with the district optimization, trusting the results, we can purely realize that proper envelopes and windows refurbishment would eliminate massively the thermal comfort lacks.

The best retrofitting solution obtained involves a centralized AC system with an air heat pump, powered by a photovoltaic-thermal system. With 25 kWh/m2 × yr, the simulated energy demand is fully within the standards of a Nearly-zero building, and even less than Portuguese Passivhaus observed. Furthermore, a third of the demand is fed by solar resources. Moreover, further optimization not here faced is possible, reducing strongly the appliance and lights demand, with the adoption of LEDs for lighting and equipment with high-efficiency energetic classes.

Despite the fluctuation of the solar and wind power, through the huge amount of electricity produced by Portugal, the country's electrical grid could power this range of residential demand, cutting significantly the emissions.

REFERENCES

[1] “Data tables – Data & Statistics - IEA.” [Online]. Available: https://www.iea.org/data-and-statistics/data-tables?country=WORLD. [Accessed: 09-Sep-2020].

[2] Annual I.E., “World Energy Overview: 1996-2006,” *EIA Independent statistic and analysis U.S Energy Information Administration*. 2007.

[3] “Tracking Buildings – Analysis - IEA.” [Online]. Available: https://www.iea.org/reports/tracking-buildings#. [Accessed: 02-May-2020].

[4] “The Sustainable Development Agenda – United Nations Sustainable Development.” [Online]. Available: https://www.un.org/sustainabledevelopment/development-agenda/. [Accessed: 19-Nov-2020].

[5] UNEP, “Towards a Green Economy. Pathways to Sustainable Development and Poverty Eradication,” 2011.

[6] European Commission, “A Clean Planet for all - A European long-term strategic vision for a prosperous , modern , competitive and climate neutral economy,” *Com(2018) 773.*, p. 114, 2018.

[7] “Lisbon Population 2020 (Demographics, Maps, Graphs).” [Online]. Available: https://worldpopulationreview.com/world-cities/lisbon-population. [Accessed: 24-Sep-2020].

[8] UNITED NATIONS - DEPARTMENT OF ECONOMIC AND SOCIAL AFFAIRS, “68% of the world population projected to live in urban areas by 2050, says UN | UN DESA | United Nations Department of Economic and Social Affairs,” *United Nations News*. 2018.

[9] EPUL – EMPRESA PÚBLICA DE URBANIZAÇÃO DE LISBOA and CML – CÂMARA MUNICIPAL DE LISBOA, “PLANO DE URBANIZAÇÃO DO VALE DE SANTO ANTÓNIO- PROPOSTA DE PLANO-VOLUME III,” 2011.

[10] EPUL – EMPRESA PÚBLICA DE URBANIZAÇÃO DE LISBOA and CML – CÂMARA MUNICIPAL DE LISBOA, “PLANO DE URBANIZAÇÃO DO VALE DE SANTO ANTÓNIO-RELATÓRIO,” 2011.

[11] “The World’s Best Climate and Weather in 2020 - Top 5 for Retirement.” [Online]. Available: https://internationalliving.com/the-best-climates-in-the-world/. [Accessed: 25-Sep-2020].

[12] “climaplus.” [Online]. Available: http://climaplusbeta.com/OUTDOOR#secWindRose. [Accessed: 19-Sep-2020].

[13] J. D. Healy, “Excess winter mortality in Europe: A cross country analysis identifying key risk factors,” *J. Epidemiol. Community Health*, vol. 57, no. 10, pp. 784–789, Oct. 2003, doi: 10.1136/jech.57.10.784.

[14] PMEET, “Long-Term Strategy for Carbon Neutrality of the Portuguese Economy by 2050 - Roadmap to Carbon Neutrality 2050,” vol. R 262/2019, 2019.

[15] ADENE – Agência para a Energia; DGEG – Direção Geral de Energia e Geologia; Observatório da Energia, *Energia em Números- Edição 2019*. 2019.

[16] INE, “Consumo de Energia no Sector Doméstico Resultados Preliminares do Inquérito ao Consumo de Energia no Sector Doméstico 2010 Enquadramento Consumo de energia no sector doméstico (Balanço Energético) Inquérito ao Consumo de Energia no Sector Doméstico - 20,” vol. 2010, no. 1, pp. 1–7, 2011.

[17] Eurostat, “Energy, transport and environment statistics,” 2019.

[18] I. I.P and DGEG, *Inquérito ao consumo de energia no setor doméstico 2010*. 2011.

[19] A. Hermelink, S. Schimschar, and T. Boermans, “Towards nearly zero-energy buildings Definition of common principles under the EPBD Final report-Executive Summary,” 2013.

[20] “Green City | Friburgo Turismo.” [Online]. Available: https://visit.freiburg.de/it/friburgo-un-emozione-tutta-da-provare/green-city. [Accessed: 30-Nov-2020].

[21] M. Ferrando and F. Causone, “An overview of urban building energy modelling (UBEM) tools,” doi: 10.26868/25222708.2019.210632.

[22] T. Hong, Y. Chen, X. Luo, N. Luo, and S. H. Lee, “Ten questions on urban building energy modeling,” *Build. Environ.*, vol. 168, no. October 2019, 2020, doi: 10.1016/j.buildenv.2019.106508.

[23] “About ArcGIS | Mapping & Analytics Platform.” [Online]. Available: https://www.esri.com/en-us/arcgis/about-arcgis/overview. [Accessed: 19-Nov-2020].

[24] C. F. Reinhart, T. Dogan, J. A. Jakubiec, T. Rakha, and A. Sang, “UMI - An urban simulation environment for building energy use, daylighting and walkability,” *Proc. BS 2013 13th Conf. Int. Build. Perform. Simul. Assoc.*, no. July 2014, pp. 476–483, 2013.

[25] “Urban Modeling Interface | MIT Sustainable Design Lab.” [Online]. Available: http://web.mit.edu/sustainabledesignlab/projects/umi/index.html. [Accessed: 19-Jul-2020].

[26] “UMIverse | MIT Sustainable Design Lab.” [Online]. Available: http://web.mit.edu/sustainabledesignlab/projects/UMIverse/UMIverse.html. [Accessed: 24-Sep-2020].

[27] C. Reinhart, C. Sousa Monteiro, C. C. Davila, A. Arsano, I. Turan, and K. Benis, “A new Look At Old Buildings.”

[28] S. Letellier-Duchesne, P. Gianniou, and S. Nagpal, *Lisbon Gr.02*. 2017.

[29] Y. Chen, T. Hong, and M. A. Piette, “Automatic generation and simulation of urban building energy models based on city datasets for city-scale building retrofit analysis,” *Appl. Energy*, vol. 205, no. August, pp. 323–335, 2017, doi: 10.1016/j.apenergy.2017.07.128.

[30] Y. Chen, T. Hong, X. Luo, and B. Hooper, “Development of city buildings dataset for urban building energy modeling,” *Energy Build.*, vol. 183, pp. 252–265, 2019, doi: 10.1016/j.enbuild.2018.11.008.

[31] Y. Chen and T. Hong, “Impacts of building geometry modeling methods on the simulation results of urban building energy models,” *Appl. Energy*, vol. 215, no. February, pp. 717–735, 2018, doi: 10.1016/j.apenergy.2018.02.073.

[32] “CityBES.” [Online]. Available: https://citybes.lbl.gov/. [Accessed: 24-Sep-2020].

[33] “City Building Energy Saver (CityBES) | Energy Technologies Area.” [Online]. Available: https://eta.lbl.gov/resources/software/city-building-energy-saver. [Accessed: 19-Jul-2020].

[34] “CityBES: City Building Energy Saver | Best Directory.” [Online]. Available: https://www.buildingenergysoftwaretools.com/. [Accessed: 29-Nov-2020].

[35] D. Robinson, “CITYSIM: COMPREHENSIVE MICRO-SIMULATION OF RESOURCE FLOWS FOR SUSTAINABLE URBAN PLANNING,” 2009.

[36] “CitySim Software – LESO-PB - EPFL.” [Online]. Available: https://www.epfl.ch/labs/leso/transfer/software/citysim/. [Accessed: 24-Sep-2020].

[37] P. Remmen, M. Lauster, M. Mans, T. Osterhage, and D. Müller, “CITYGML IMPORT AND EXPORT FOR DYNAMIC BUILDING PERFORMANCE SIMULATION IN MODELICA.”

[38] “GitHub - RWTH-EBC/TEASER: TEASER - Tool for Energy Analysis and Simulation for Efficient Retrofit.” [Online]. Available: https://github.com/RWTH-EBC/TEASER. [Accessed: 24-Sep-2020].

[39] R. Nouvel, E. Duminil, V. Coors, and U. Eicker, “SimStadt, a new workflow-driven urban energy simulation platform for CityGML city models.”

[40] “SimStadt2.” [Online]. Available: https://simstadt.hft-stuttgart.de/en/index.jsp. [Accessed: 24-Sep-2020].

[41] J. A. Fonseca, T. A. Nguyen, A. Schlueter, and F. Marechal, “City Energy Analyst (CEA): Integrated framework for analysis and optimization of building energy systems in neighborhoods and city districts,” *Energy Build.*, vol. 113, pp. 202–226, Feb. 2016, doi: 10.1016/j.enbuild.2015.11.055.

[42] “City Energy Analyst (CEA).” [Online]. Available: https://cityenergyanalyst.com/. [Accessed: 24-Sep-2020].

[43] “ADENE - Agência para Energia - ADENE.” [Online]. Available: https://www.adene.pt/. [Accessed: 19-Nov-2020].

[44] E. P. Tomasini, *Misure e Controlli Termotecnici*. 2016.

[45] “Diagrama Bioclimático de Givoni – ARQUITECTURA EFICIENTE.” [Online]. Available: https://pedrojhernandez.com/2014/03/03/diagrama-bioclimatico-de-givoni-2/. [Accessed: 30-Nov-2020].

[46] S. Vadoudi, Kiyan Marinhas, “Development of Psychrometric diagram for the energy efficiency of Air Handling Units,” *Eurovent Certita Certif.*, pp. 491–500, 2018.

[47] “Indici di Comfort Termico: Fanger PMV, Modello Adattivo e Diagramma Bioclimatico di Givoni.” [Online]. Available: https://www.mygreenbuildings.org/2009/12/29/indici-di-comfort-termico-fanger-pmv-modello-adattivo-e-diagramma-bioclimatico-di-givoni.html. [Accessed: 30-Nov-2020].

[48] “Associação Passivhaus Portugal.” [Online]. Available: http://www.passivhaus.pt/sobre?m=2. [Accessed: 17-Sep-2020].

[49] “Passive House Buildings.” [Online]. Available: https://passivehouse-database.org/index.php?lang=en#d_2403. [Accessed: 17-Sep-2020].

[50] A. Revi, D. E. Satterthwaite, F. Aragón-Durand, and J. Corfee-Morlot USA, “Urban areas,” William Solecki.

[51] Enat, “NÓS CONHECEMOS A ENERGIA DA NATUREZA.” 2018.

[52] POSEUR, *Custos-padrão máximos por tecnologia definidos pela DGEG Os*. 2020.

[53] “Ductless Mini-Splits vs. Central Air: Pros and Cons | Fire & Ice.” [Online]. Available: https://indoortemp.com/resources/mini-split-vs-central-air-pros-cons. [Accessed: 24-Sep-2020].

[54] “CO2 emissions per m2 for space heating — European Environment Agency.” [Online]. Available: https://www.eea.europa.eu/data-and-maps/figures/co2-emissions-per-m2-for-1. [Accessed: 24-Sep-2020].

[55] “efficienza energetica edifici.” [Online]. Available: http://alessandroperbellini.it/efficienza-energetica/. [Accessed: 06-Dec-2020].

[56] “Ductless vs. Ducted Heat Pumps | Newcomb and Company.” [Online]. Available: https://www.newcombandcompany.com/resources/ductless-vs-ducted-heat-pumps. [Accessed: 16-Nov-2020].

[57] "Acqua calda sanitaria: qual è la soluzione migliore per averla gratis o quasi?" [Online]. Available: http://www.riqualificazione-energetica.net/acqua-calda-sanitaria-qual-e-la-soluzione-migliore-per-averla-gratis-o-quasi/. [Accessed: 16-Nov-2020].