Life Cycle Cost Analysis of HVAC systems in office buildings

The Case Study of EDP real estate

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Thesis to obtain the Master of Science Degree in

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RESUMO

O trabalho realizado na presente dissertação pretende simular uma situação com que um técnico se pode deparar na gestão de ativos físicos, designadamente na gestão da componente energética de edifícios. A questão em causa incide sobre a tomada de decisão relativamente à gestão de sistemas de climatização em edifícios tendo em consideração todo o ciclo de vida dos mesmos. Neste contexto, a investigação procurou analisar dados operacionais de edifícios reais para modelar os custos na fase de utilização, tipicamente os mais incertos dada ser a fase do ciclo de vida mais extenso e simultaneamente mais variável. O objetivo final é estimar os custos do ciclo de vida dos sistemas para avaliar a viabilidade da sua substituição.

A dissertação inclui a explicação detalhada dos sistemas HVAC, descrevendo como eles são categorizados, os principais componentes e as várias soluções que podem ser instaladas. Depois disso, foi apropriado ilustrar os estudos de caso, em seguida, todos os principais edifícios e características da planta que afetam a escolha do novo sistema que pode substituir o existente. Foi também descrito o método da análise dos custos do ciclo de vida utilizado para os cálculos, com todos os pressupostos adotados e a motivação para trás, tendo sido realizada uma análise de sensibilidade no estudo, para melhor captar a variabilidade dos componentes-chave que afetam os resultados da LCCA.

Finalmente modelaram-se os custos do ciclo de vida dos sistemas de climatização num conjunto de edifícios de escritórios espalhados pelo território continental de Portugal, cuja localização coincide com os locais onde a maioria da população está concentrada e cobrindo um leque alargado de condições climáticas.

Palavras-chave: sistemas de climatização em edifícios; análise de custo do ciclo de vida; Análise de sensibilidade.

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ABSTRACT

The work done in this type of thesis is comparable to a real assignment that can happen habitually to an engineer in the field of energetics in the building sector. Especially, this dissertation focused on carrying out an analysis of the costs foreseen during the whole life cycle of HVAC systems for a particular typology of construction, i.e. buildings of medium and large size used for office.

In particular, this study was commissioned by EDP Distribuçao, which intends to know the Life-cycle cost analysis of HVAC systems that could replace those already operating in ten offices located throughout Portugal in order to improve energy efficiency and reduce energy costs.

Initially, it was indispensable to explain in detail what are the HVAC systems, describing how they are categorized, the main components and the various solutions that can be installed. After that, it was appropriate to illustrate the case studies, then all the main buildings and plant characteristics that affect the choice of the new system that can replace the existing one.

Subsequently, was described the LCCA method used for the calculations, with all the assumptions adopted and the motivation behind. Therefore, a sensitivity analysis was inserted in the study, to better capture the variability of the key components that are affecting the LCCA results.

The last part of the thesis was dedicated to the comments of the results obtained and to the suggestions that arose, explaining why is necessary or not to substitute the HVAC systems present in the offices.

Key-words: heating, cooling and ventilation systems in buildings; Life-cycle cost analysis; Sensitivity analysis.

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INDEX OF CONTENTS

INDEX OF FIGURES

INDEX OF TABLES

INDEX OF ANNEX TABLES

ABBREVIATIONS AND ACRONYMS

MONETARY UNIT

€	Euro

OTHER

LCCA	Life-Cycle Cost Analysis
HVAC	Heating Ventilation and Air Conditioning
PV	Present Value
FV	Future Value
LCC	Life-Cycle Cost
CAV	Constant Air Volume
VAV	Variable Air Volume
VRF	Variable Refrigerant Flow
IC	Investment Cost
O&M	Operations and Maintenance
EC	Energy Cost
MC	Maintenance Cost
RC	Repair Cost
CAPEX	Capital Expenditure
E_a	annual Energy consumption
P_{elec}	electricity Price
P_{nom}	nominal Power
P_{out}	output Power
h_a	annual utilization factor
EER	Energy Efficiency Ratio
COP	Coefficient of Performance

U	Thermal transmittance
SA	Sensitivity Analysis

1 INTRODUCTION

1.1 CONTEXT

Energy is consistently reported as an essential resource for modern societies. The population growth and lifestyle changes have been and still are increasing the energy demand and there have been various economic (e.g., energy crisis in the 1970's), environmental (e.g., pollution from fossil fuels use) and social (e.g., armed conflicts over energy sources control/access) impacts.

The energy consumed globally in buildings makes up the largest portion, accounting for 40% of the total energy consumed worldwide (Gruber et al., 2015). This also corresponds to 38% of the greenhouse gas emissions, reflecting the dimension of the issue both from an economic and environmental perspectives. In Portugal, the energy consumption in buildings averages 25% of the national total, but in urban areas the proportion can be up to 40% (Correia Guedes et al., 2009). Generally, space heating and cooling (HVAC) tends to be the most significant energy end-use in buildings in most countries (Figure 1). Considering that climate changes are forecasted to increase extreme weather events, namely cold fronts and heat waves, the need for HVAC systems in building will tend to increase in the future in order to keep the living standards.

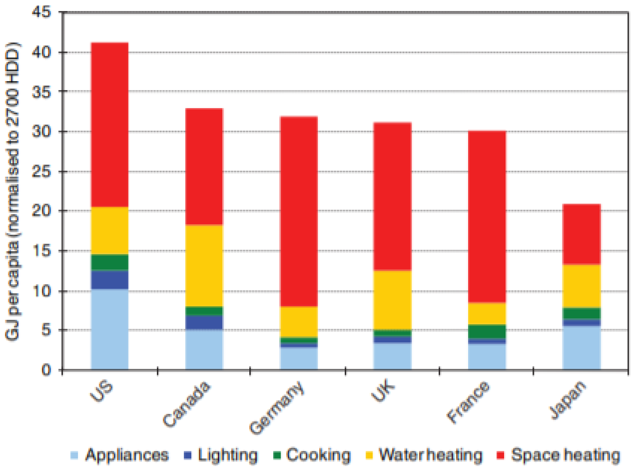


Figure 1: Energy consumption amongst different purposes in residential buildings (Ürge-Vorsatz et al., 2014)

To tackle the energy demand challenge, there have been significant advances at several levels, in particular the technological level. In fact, energy efficiency in buildings became an explicit priority in the EU with the energy rating of buildings and that as boosted the development of technological solutions.

Within the various components of a building, an HVAC system is becoming an increasingly essential one. Nowadays, HVAC systems are present in any type of building, including commercial, hotels, schools, offices, hospitals or households. These systems not only account for the largest portion of the building energy consumption in most cases, but they can also occupy a large space in some cases and have a high initial investment. Therefore, it is important to have the correct size and design project for the specific needs to contribute to a successful energy-efficient building. Oversizing the system is harmful to the building, in particular to the equipment durability, energy use, indoor air quality, and comfort, because the system will be short cycling in both cooling and heating modes. An HVAC system should be designed to work for a long time to reach the peak operational efficiency and avoid excess humidity present in the conditioned air distributed to the room, that can make mold inside the building. Therefore, starting and stopping often the system can cause an early failure of the equipment.

However, buildings and building components alike tend to have large useful lives, making their renewal slow. Considering that the investments are significant, concentrated on time and certain, while benefits are dispersed over time and more uncertain, the viability of investing in such technologies are not immediate in many cases.

The present thesis analyses the operational data of real office buildings to evaluate the life cycle costs (LCC) of HVAC systems, providing some basis for future studies on the viability of replacing existing systems by more energy efficient ones based using a proactive approach instead of a reactive approached based on the design life of 20 years usually adopted.

1.2 SCOPE AND OBJECTIVES

Office buildings are one of the types of buildings where the energy consumption for heating and cooling makes up a large fraction of the total. Considering the influence of thermal comfort on productivity, the concentration of people and electronic equipment and the number of hours that the building is occupied each day, HVAC systems are virtually present in any medium to large office building in Portugal. The present thesis analyses the LCC of the HVAC in 10 offices in the cities of Penafiel, Porto, Guarda, Coimbra, Leira, Lisbon and Faro.

The general objectives of the thesis are therefore:

- quantify the costs of the HVAC systems and their life cycle in the offices and try to discretize the relative cost of the various components of the systems including the new system initial costs to substitute the installed ones, operation costs (energy costs), maintenance costs (ordinary and extraordinary) and end of life of the system (salvage value)
- quantify and verify how the variability of some factors affects the result of the analysis

1.3 METHODOLOGY

The methodology used comprised on applying a Life Cycle Cost Analysis (LCCA) to the case studies, complementing the existing data with bibliographic and supplier's information. LCCA is a method that consists in analysing all possible costs to be addressed during the life cycle of a product/process or activity. For this specific case, it had to be applied to a product, which is the HVAC system. The applied method is essentially to calculate as accurately as possible, the sum of future costs discounted at today. The discount rate represents the return of alternative investment or the cost of borrowing money, which in this case base is the risk-free rate, determined by the yield of a ten-year bond. This yield is then inserted in the formula (1.3) to all future costs, to have today's value.

$$PV = \frac{FV}{(1+r)^n} \tag{1.3}$$

Where:

PV - present value of cost

FV - future value of cost

r - discount rate

n - number of periods

Being that some variables estimated in the LCCA are uncertain, it is advisable to insert a sensitivity analysis to better capture the outcome of different alternative scenarios that may occur.

1.4 THESIS ORGANIZATION

In addition to the present chapter, the thesis encompasses 4 more chapters:

- in Chapter 2 the topic of HVAC systems is discussed, describing the importance they have within the building, how they are classified and the main components that compose them. It is then examined which are the various types of systems on the market;
- in Chapter 3 there is a description of the offices investigated, analysing all those elements that influence the choice of the HVAC system, such as the location, the climatic conditions, the size of the building, the transmittance values of the main opaque and transparent structures. The HVAC systems currently operating in buildings are also analysed. Subsequently, the methodology applied is explained;
- in Chapter 4 the results obtained by the LCCA analysis are presented;
- in Chapter 5 the results are commented out and the conclusion of the thesis is completed.

2 STATE OF ART

2.1 GENERAL CONSIDERATION

In the design phase of the construction of a new office building, it is crucial to identify the right HVAC equipment size to meet heating/cooling peak demand.

The wrong design of the HVAC system can have a significant impact on the overall cost of the system (initial and operating costs) during its life-time, leading to a non-necessary increment of energy and operating costs. Is it to note that HVAC represents on average 11% of the office building construction cost (Plotner, S., et al. 2017).

In the 2nd Chapter, describing the HVAC systems, the following topics are discussed:

- Characteristics and classification of the HVAC systems
- Analysis of the three main components (source, distribution, and delivery) that constitute the centralized system
- Analysis of the three most used HVAC system solutions (all-air, all-water, air-water)
- Life-cycle costing of an HVAC system

2.2 OVERVIEW OF AN HVAC SYSTEM

HVAC (Heating Ventilation and Air Conditioning) system is the equipment that provides heating, cooling, humidity control and it can filter outdoor air to preserve comfort conditions in a building, by controlling the air quality and the air circulation (ARSHAE, 2012).

The main goal of an HVAC system is to supply indoor thermal conditions that can satisfy the majority of the occupants.

It is not always necessary for the temperature to increase or decrease, but only to have an adequate air velocity that allows the skin to have correct evaporation, avoiding excessive sweating. However, usually, the system is used to add or remove heat to or from the building spaces, to reach the standard internal thermal comfort. As a rule, it removes moisture from the room in the summer and adds it in the winter.

The moisture and heat control functions of an HVAC system can be defined as a key system component. On the other side, air quality control and air circulation are the additional functions of the system.

Each building has its own balance point temperature, which is a certain external temperature that allows to have inside the building an optimum temperature that guarantees comfort without the use of other systems. This balance point temperature varies from building to building because it depends on the overall heat coefficient of the building envelope.

If the outside temperature is below the balance point temperature, a heating system will be used to avoid heat loss through the building envelope. Vice versa, when the outside air temperature is above the balance point temperature, a cooling system is needed to maintain a good level of comfort for the occupants. Nowadays, the market offers to its consumers a great variety of HVAC system technologies, able to satisfy every type of needs based on the use of the edifice.

With the regulation in force, the HVAC system needs:

- To be environmentally friendly
- To have a monitoring and control system of internal parameters to avoid energy waste and keep the level of temperature and humidity within required limits
- To select high energy efficiency, low consumption, and cost-effective equipment
- Minimize the contribution of the global warming effect and ozone depletion
- To make sure that the system receives adequate maintenance and that they are constant during the lifetime
- To have appropriate fire protection and smoke control systems

In the design phase of a building, one of the most important phases is the choice of the type of HVAC system. There are a multitude of plants based on every kind of need, for example, a system for a small shop may not be the best choice for a condominium. In the decision process, it has to be taken into consideration plant size, the use of the building, the location (therefore climatic conditions), the typology of the building, etc.

To ensure that the system satisfies the occupants needs, it is important to have a good control of the system. This is a crucial fact that introduces the concept of zoning. In the design phase of the HVAC system, a zone is essentially a portion of the building that needs to have its own control system. The ideal is to have a control system available in every room. In fact, a zone can be immediately identified as an area that is managed by a single control point, usually represented by a thermostat. The division of the thermal zones needs to be established during the planning phase (ARSHAE, 2012).

The most common standard HVAC systems can be defined as “active”, because they need an external energy input to work. They have specific components like boilers, chillers, air duct, and fans, that are independent of other building functions (ARSHAE, 2012).

Contrarily, the HVAC “passive systems” are less used, but they are usually more energy efficient. It is frequent to find it in a new construction because these systems exploit the natural ventilation, the radiative heating, and the evaporating cooling. Moreover, they use natural resources for energy inputs that are generally conveyed by specific construction´s parts and strictly related to the building design project. For this reason, can be hard to install a passive system in an existing edifice without structurally intervening, and without reaching high installation costs (ARSHAE, 2012).

It can be classified in two main categories: centralized system or decentralized system.

2.2.1 DECENTRALIZED SYSTEM

Local or decentralized system is used for small or medium-sized installations. They usually handle only one space and are placed directly inside or adjacent to the room.

They can be formed by one or more single HVAC units, each having a heat source or integral refrigeration cycle and direct or indirect external ventilation. They do not have ducts or pipes for the transport of the energy, the production, and the delivery take place directly from the system itself. These systems are easy to install and low-cost. The components are assembled in order to achieve the desired performance and have independent zone control systems. Care should be taken when choosing its position within the room so that the system distributes the energy within the space in the point with the most efficient outcome (ARSHAE, 2012).

The disadvantages compared to the centralized system are that these systems have shorter useful lives and are less efficient.

2.2.2 CENTRALIZED SYSTEM

The centralized system needs more space and/or more planes or more thermal zones from a single source.

They are very versatile and adaptable to any building, from individual dwellings to condominiums, but it is particularly suitable for much larger buildings like schools, hospitals, offices, shopping centers, etc., where there is a high density of energy consumption (Figure 2). There are many possible configurations for the plant, depending on any type of situation, location, budget available, use of the building, used refrigerant, etc.

The system requires special attention in the design process, since more complex than the decentralized one, as it is necessary to foresee a correct and adequate positioning of each element inside the building, despite this system being very flexible.

Nevertheless, large plants usually have high installation costs, but they are also very efficient and offer a better control of the comfort conditions. In this regard, they can have various control points (thermostats) arranged at different points of the heated or cooled space, to control and/or regulate the temperature and humidity (ARSHAE, 2012).

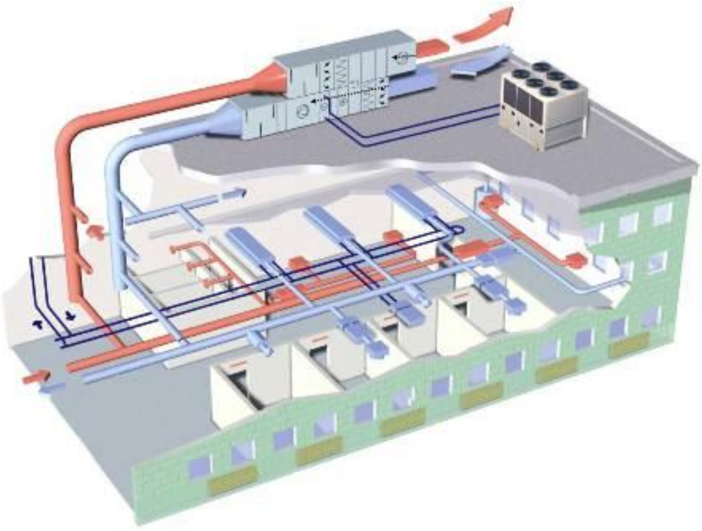


Figure 2: Centralized HVAC system *(browntechnical.com)*

2.3 HVAC COMPONENTS OF A CENTRALIZED SYSTEM

Unlike local systems, centralized ones are more complex and have different elements that can be divided into three functional categories (Grondzik & Furst ,2000):

- Source components
- Distribution components
- Delivery components

Most of these systems use boilers or chillers to generate the energy needed to produce or remove heat from the premises, being these elements installed either inside the building and in some cases in a special room, or for large plants, on the roof.

2.3.1 SOURCE COMPONENTS

The source components remove or provide heat or moisture (Grondzik & Furst, 2000).

The heat in the building can be generated mainly from four types of heat sources. One of these can come from the combustion of flammable material such as wood, natural gas or coal, so by a fuel. Another way is that the heat may be collected in the site using a renewable energy source usually by solar radiation and converted. Moreover, it is also possible to remove heat from specific materials in loco and transfer it inside the building. Lastly, heat can be converted through the electric resistance’s process.

On the contrary, the cooling is produced by a reverse heat flux. A passive cooling system works with the natural heat sinks, for instance, the external air with its sensible and latent condition, temperature and humidity respectively; or by the night sky, on-site soil, and on-site water bodies. Despite this, it is not always possible to exploit the natural heat sinks and their use may be limited by the availability and/or capacity of the resources.

Choosing to opt for an active cooling system can be more immediate and simpler since they offer stable performance over time. This is because, active system heat sinks work with external energy input, in particular with some type of refrigeration device.

Three main types of refrigeration technics are employed in a building: mechanical refrigeration with vapour compression, chemical refrigeration through the absorption and evaporative cooling. The choice of a source component is made by the availability of the resource, fixed budget, energy needed and based on the context of the building (Grondzik & Furst, 2000). Since the goal of this thesis is to study a feasible HVAC solution for some office buildings, then only the components that are compatible with these types of edifices are elaborated.

Boiler: it is a heating component used to heat usually water for distribution to the building spaces. Since the water cannot be used directly to heat the spaces, boiler works in the central systems where the water is firstly heated and then distributed to the building with the help of the delivery devices. It generally uses three types of heating sources: electrical resistance, combustion (oil, coal, natural gas, propane) and in combination with a renewable energy system. The boiler is formed basically by a heat-source element (electric or burner resistance coil) and a certain amount of water storage. Moreover, it may produce either stream or hot water. In some conditions and cases, it can be substituted with a solar energy system or with a heat transfer system (heat pumps) (Grondzik & Furst, 2000).

Solar thermal collector: it is a specific component for the heating system and can be used to heat water or air. As above mentioned, it may integrate or substitute a boiler in the water-based heating system. It cannot be considered a working component at any time since it exploits renewable energy, and it can only be used during the daylight. During the night, it needs external help to work properly in the heating system. Moreover, solar thermal collector can be used for cooling if combined with an absorption refrigeration system (Grondzik & Furst, 2000).

Compression refrigeration unit: it is the most regularly used active cooling method and it is basically installed in a central application system. This approach induces heat to go in the opposite direction to the differences in gross ambient temperatures. When the outside temperature is above the temperature of the equilibrium point, in order to maintain the condition of thermal comfort in the spaces, the heat must be removed. By artificially pre-setting the pressure and temperature with the heat exchange fluid (refrigerant), a refrigeration system is able to flow the heat from inside the building to the outside, thanks to the operation of four primary components of the system: a steam compression unit, that acts as a heat sink between the flow of a refrigerant into a fixed circuit and a compressor, which provides energy to the refrigerant. A condenser that cools the refrigerant with water or air for conduction, allowing the refrigerant to pass from the gaseous to the liquid state and then release a considerable amount of heat which is absorbed by the water flowing into the capacitor. In an expansion valve, the coolant loses pressure and a part of the liquid evaporates in order to reach the evaporator, where all the residual coolant is transformed into gas. This process causes the environment to refresh itself and can be used as a heat sink in buildings (Grondzik & Furst, 2000).

Evaporative cooling unit: it is a perfect and efficient technology in the hot dry climates. This is a psychrometric process where the air is cooled and humidified at the same time. It uses a ventilator to capture the dry air, this one passes through some porous materials that are wet with water. In this phase, the air contacts the water and part of the water evaporates. The energy needed to evaporate the liquid comes from the air. Then the air passes through a cooling unit and here, is humidified and cooled too (Grondzik & Furst, 2000).

Chiller: this component is usually chosen for large buildings. The chiller cools the space by using cold (chilled) water. This is then distributed by cooling coils placed in the air movement units, induction units or fan coils. By changing the flow of water with the coils, you can control the capacity of this system. The chillers can work with both the absorption and the steam compression principle (Grondzik & Furst, 2000).

Figure 3: Air-cooled Chiller *(Daikin.com)*

Cooling tower: this component is a heat rejection device. It is installed outside the building, allowing the heat to be diffused into the water of the condenser. The liquid used is considered as a heat exchanger between water and refrigerant. In fact, it increases the water temperature, which must then be cooled to allow the cycle to continue. The condenser´s water then arrives into the tower, where the evaporative cooling removes heat from it and is placed in the outside air. Then, the cold water of the condenser reaches the cooler. The cooling tower swaps and works with latent heat (Grondzik & Furst, 2000).

2.3.2 DISTRIBUTION COMPONENTS

The distribution components connect the source with the delivery components, transporting heating or cooling medium in the building (Grondzik & Furst, 2000).

These components are always used in the central system since they have the production of the cooling and/or heating effect in a single point of the house. Then this effect is distributed in the various environments. The ways of transmission are usually the water, the air, and the steam.

When the system uses water as a medium, the distribution components used are the pipes, taking at least two of them: one for the water supply and the other for the return water. In this context, closed circuit systems are widely used as they are cheap during the heating and cooling phase. The use of only two tubes occurs in those cases where only the heating system has to be installed or vice versa or when is necessary to install both three or four pipe distributions with the aim to increase the flexibility of the system. A three-tube system consists of two supply pipes, one for cold water, one for hot and a single return. Is to be noted that, only one pipe for the return is not efficient and therefore not recommendable. For this reason, a common practice is to adopt the solution with four tubes which have two supply and two return pipes, allowing the separation of the heat from the cold, in favour of more flexibility and efficiency.

The material chosen for the tubes is usually steel, or copper when conditions allow. The pipes are insulated to ensure that they do not have large temperature losses on the traveling route. Many accessories are adopted in HVAC piping systems, such as flow control valves, pressure gauges and one or more pumps that allow the water thrust to circulate it in the system, overcoming friction losses (Grondzik & Furst, 2000).

Ducts are used for centralized air systems (channelling). As for water systems, are needed at least two ducts, one supply and one for return. In the air distribution loops, is possible to recirculate the internal air, offering an economical solution to heat or cool the return air compare to the usage of new external air. However, the latter must be introduced often in the system to maintain the good quality of the internal air, while the return air must be returned to the outside by means of special devices (Grondzik & Furst, 2000).

The channelling systems can be classified in different ways. Based on the speed of the flow, there are high or low-speed systems, or depending on the static pressure, high- or low-pressure systems. Almost always the supply duct has low pressure and low speed as the duct section decreases along with the distribution path, and in buildings with reduced spaces, the speed increases. The return duct has the same characteristics as the delivery one, caused by the higher energy expenditure needed by high pressures (Grondzik & Furst, 2000).

The duct is made from sheet metal (galvanized steel) with fiberglass edge. Plastic on a spiral metal structure for flexible ducts is also used. On the market, is possible to find cross sections of the rectangular, square, oval and circular channels. In particular, the most economical and efficient form is round, as it reduces friction losses while being the rectangular section the most adaptable to spaces. All channels must be well sealed in order to have less possible load losses while the return duct is usually not isolated (Grondzik & Furst, 2000).

For channelling systems, the accessories include shock absorbers, rotating blades, and dividers. The shock absorbers control and balance the air flow. The other two accessories are used to reduce the friction losses by decreasing the turbulence in the ducts. One or more fans are used to provide air input to traverse the ducts depending on the size of the system. Finally, very important are the air handling units, to ensure that good air quality is ensured for the occupants (Grondzik & Furst, 2000).

2.3.3 DELIVERY COMPONENTS

The delivery components are the final elements of the system and are those who interface directly on the spaces to be heated or cooled. Air or water previously cooled or heated and transported to environments, cannot be placed directly into spaces without control of the distribution (Grondzik & Furst, 2000). To meet this requirement there are delivery devices and some of them will be discussed later.

Diffuser: is a device that is part of the air systems which serves to introduce air into environments. It is usually carefully selected as it is installed in the ceiling, allowing the occupants to see it. Diffusers of various shapes, sizes and capacities are commercially available, adaptable to all requirements (Grondzik & Furst, 2000).

Grille: They serve substantially to cover the openings of the return air. They are purely aesthetic and decorative components (Grondzik & Furst, 2000).

Register: They are similar to the diffuser, but they are installed for the supply of air for the hips or for the floors, or as accesses for the return air (Grondzik & Furst, 2000).

Baseboard Radiator: is a delivery component for water or steam systems. Visually, they are similar to the electric resistance skirting unit. They are finned tubes that exchange heat in the room through conduction, thus heating the air inside the room (Grondzik & Furst, 2000).

Radiant Panels: They are used for water or steam systems. They can be of two types: radiators that are exposed devices installed on the walls or on the floor, which is a pipe inserted in a layer of the floor, covering all the surface, where it flows hot water that heats the air of the environment to lead. The latter is not visible directly by the occupants as it is placed inside the floor (Grondzik & Furst, 2000).

2.4 HVAC SOLUTION SYSTEMS

The HVAC systems, in addition to being able to be divided into DSSP or centralized system, can be classified according to the working fluid used within the system (Gheji, 2016). In this case, it is possible to have:

- All-air system
- All-water system
- Air-water system

2.4.1 ALL-AIR SYSTEM

It can be inferred from the name that this system uses air as a media. They are commonly adopted in new buildings and existing ones. Fundamentally, they can be divided into two main categories: single or multizone. For both, is possible to find systems with constant or variable volume or with single or double duct (Gheji, 2016).

The main concept of all-air systems is to dispense air into space so that the latent and sensitive heat reaches temperature and humidity conditions in line with the comfort levels ideal for the occupants. In order to maintain the desired conditions within the environment, the system has two types of mechanisms in which is possible to act: vary the air temperature supplied to space and change the amount of air distributed. The choice of the characteristics of the system should take into account the function, the physical characteristics of the building and the environment, meaning the thermal exchange capacities required and the quantity of air volume to be heated/cooled.

The Air system not only can be used to heat or cool but also to humify or dehumidify the environment. It can be adapted to many applications, from smaller buildings to the most imposing ones with a large space to be heated or cooled. They can offer the possibility of having individual automatic control for each terminal in such a way as to ensure the supply of the desired air quality for the space (Grondizik, 2007).

It is also possible to have different heated areas in the same room. For example, the areas adjacent to the perimeter wall that borders the exterior may need more thermal energy than the centre of the room and for large surfaces, it is possible to have different heat supplies. To increase the heating or perimeter cooling is viable to opt for a separate additional system, such as a skirting system or overhead.

It is important to consider the air supply temperature, in the design phase of the system. The choice may be based on external weather conditions, on the size of the system or on the intended use of the rooms. Depending on the air supply temperature, it is essential to carefully choose all the right components for a good functioning of the system, considering an adequate ventilation and air handling within the environment, in order to avoid problems of condensation, ill-smelling, or simply bad air quality.

Generally, systems that work at low temperature, are in some cases more advantageous, as they provide lower levels of humidity in the rooms and less energy consumption at lower costs. However, in other cases, they could instead increase the overall use of energy, so it is good to carefully choose the temperature levels case by case (Westphalent, 1999).

Moreover, the air system can be divided into three components:

- Air Treatment Unit (source components), in which air is brought to the desired conditions
- Distribution system, where the air is transported from the source to the conditioned space
- Delivery system, connecting elements between the distribution system and the conditioned area

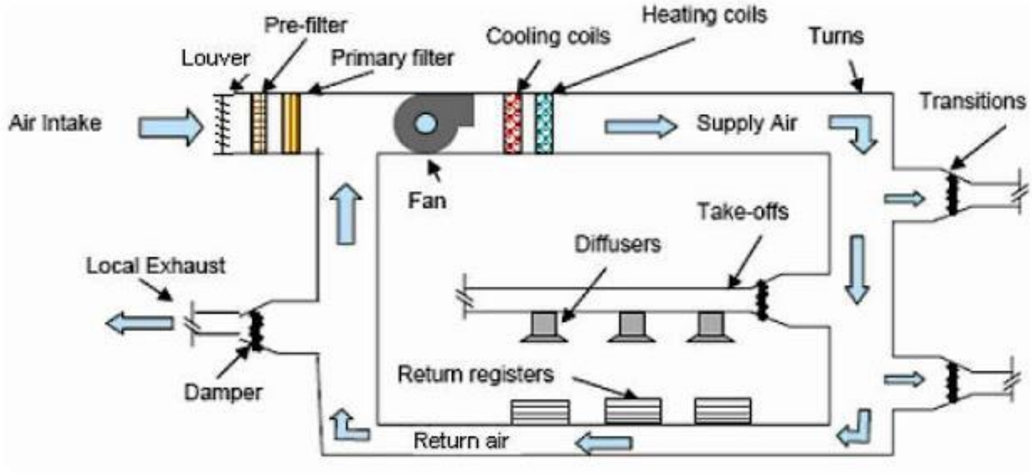


Figure 4: All-air HVAC system configuration ***(spacemepacademy.com)***

The position of the source components is chosen according to the size of the system. A small system can be placed inside the heated area while large plants are usually are situated in a designated room where there is all the necessary equipment, or in other cases may be placed on the roof of the building. The criterion of placing all the equipment in one place facilitates the maintenance of the system as less equipment is used and is put all in one position. However, the rooftop unit, when conditions permit, is the best choice because there is direct access to the external environment for heat or combustion air.

The elements used for transporting thermal energy are shock absorbers, mixing chambers, filters, coils cooling/heating, humidifiers, ventilators/blowers and for the distribution are used ducts, shutters, and diffusers.

In these systems, it is important to establish pressure and air velocity. If initially is chosen a constant high-speed airflow and smaller ducts, in order to occupy less space even at the expense of noise, it will create imbalances and problems to the system, if in the future there will be a change on the operating functions of the system, such as reducing the air speed. Therefore, in some cases, a variable flow system can be chosen, but it must be carefully designed in such a way that it works efficiently at all loads (Westphalent, 1999).

Air systems can be divided into two main categories:

- Single duct system
- Dual duct system

They can be also designed at constant volume or variable volume (VAV), single zone or multi-zone.

SINGLE DUCT SYSTEM

Single duct systems have only one supply duct and another for return. It can serve both to heat and cool the environments, but the two things cannot happen simultaneously. Most applications are for single-family residential units. There are various types of single duct system on the market: the first distinction is made for single-zone and multi-zone systems, then for both types, it is possible to share between the systems at constant volume (CAV) or variable volume the so-called VAV System.

In single duct systems at CAV, the volumetric flow rate of the supply air remains constant throughout the operating life of the system. Temperature and humidity can be changed but the air flow remains constant.

The easiest all-air system to build is the single zone as its control is based on the measurement of temperature and the relative humidity is carried out by a single point (thermostat). In case is needed to change the conditions of the space, it can be done from a single thermostat for all the entire space. However, one space is not always only related to a single room, but sometimes also to a whole floor or a whole building. One of the advantages of this plant lies in its simplicity both in design and maintenance during its useful life, and it also has a low initial cost. On the other hand, it can only affect a single area, and for more complex buildings it is not the most appropriate choice (Westphalent, 1999).

For large buildings with varying needs of temperature levels, viable to opt for a multi-zone system, which is a modification of the single zone system. With the multizone system, is possible to control the spaces for the unequal load zones and is possible to cool or heat simultaneously the perimeter zones with different exposures. This system uses a particular air handling unit, with many routes for airflow that are parallel to the cooling and heating coils. The multizone system is conceptually analogous to the dual-duct system.

The mixed air conditioning is transported in the distinct areas of the building following the same principle of the single-zone duct system. This type of plant is structured downstream in a system of ducts dedicated to the zones, while on upstream, the return air is collected in a single pipe,3 mixing the air from all the different zones.

For small low-pressure systems, it is usual to heat the coils of the ducts for each zone. In more complex designs, the high pressure for primary distribution channels is normally used to reduce costs and dimensions, and pressure reduction devices are inserted to keep the volume constant for each area of heating.

Special care must be taken during cooling, as setting too low temperatures can lead to high use of the current load, thus leading to excessive use of energy. Fortunately, is possible to vary and control the temperature of the supply air and thus reduce the energy consumption.

It is necessary to avoid the internal humidity to reach high levels when the air exits the cooling coil, but thanks to the constant volume of the system, it is possible to control the humidity of the room and/or the pressure of the space.

Correct dimensioning of the system at constant volume is important to avoid excessive heating costs in case of oversizing. Usually, constant-volume systems are less used in commercial buildings because of the existence of variable-volume systems, but they are still utilized in all those buildings (hospitals, laboratories, etc.) where the variable airflow can cause damages, e.g. infections (Westphalent, 1999).

In variable volume (VAV) systems, unlike the previous ones, the temperature of a zone can be controlled by adjusting the amount of heated or cooled air, instead of varying the level of the supply air temperature. Usually, the supply air temperature is kept relatively constant in these types of systems.

In each zone, it is possible to find a VAV box, formed by a zone damper and a thermostat. Through this box, it is possible to regulate the flow of the air flow and thanks to the thermostat turn the box on or off. They can be installed in perimeter or inside areas, using joint or different fan and temperature control systems. With the variable volume system, less energy is consumed as it is not necessary to cool the air at too low temperatures, and because is possible to use the low power fan. In particular, the most important energy saving comes from the perimeter areas where thanks to the variations of the solar load and the external temperature, it is possible to decrease the dose of supply air (Westphalent, 1999).

Despite this, it is to be considered to not to overtake the low load conditions, in order to not create problems of indoor air quality caused by poor ventilation and air distribution in the environment. In VAV systems, it is also more difficult to control humidity levels when there is insufficient air circulation since a low supply air flow and high temperatures are maintained.

The minimum air circulation can be kept, but precautions must be taken to not create inconvenience to the occupants, such as keeping a higher temperature level, recirculating the air with additional equipment or increasing the fans in such a way that have a correct air handling.

DUAL DUCT SYSTEM

In a dual-duct system, cold air and hot air can be produced and transported at the same time in spaces, since the system has the characteristic of having two separate ducts that connect the central apparatus to the conditioned spaces. For each zone, is installed at the end of the terminal ducts, the valve that allows to mix the cold and hot air, allowing to reach the right level of temperature, pressure and humidity required by the room. Also, for this system, the return air is treated in a conventional way, i.e. using only one duct.

This plant has the advantage of being able to easily add or divide existing zones, helping to have excellent control on the levels of temperature and humidity provided to the occupants, consequently, allowing the contribution to a large variety of loads in the area. On the other hand, it is possible to have a high energy consumption, a high initial cost for all the components of the system and a considerable space is required because the plant is composed of two ducts that must reach all the conditioned zones.

This and the multizone system derive basically from the same concept, with similar strengths and weaknesses. The most notable difference in the dual-duct system, is the control of the terminal, as it is more flexible and adaptable to the different needs of each space.

During the 50's and 60's, this system had his moment of greater popularity and use, and it was chosen especially for office buildings. It is demonstrated that these systems offer better performance in moderately humid climates, with external design conditions that do not exceed 26 °C and 35 °C of dry bulb and wet bulb respectively (Grendzik, 2007).

Lately, these systems are less used, since they have a high cost and excessive energy consumption. The latter problem can be solved by inserting the VAV control, reducing the amount of the delivery air during the periods of reduction of the heating and cooling loads.

Moreover, there are basically two types of dual-duct systems: constant volume and variable volume. The plants with constant volume were often used in the 80's, presenting a single fan. As of today, the most common use is with the double fan.

There are two types of single fan systems: with or without heating.

The heating fan system has two substantial differences compared to a conventional heating system: only a portion of supply air is cooled by the cooling coil, except during the cooling peak of the application. The heating is placed in the more or less central point of the fan unit and not in the individual zones.

The energy used for the dual-duct system at constant volume is greater than the VAV single-duct system. The VAV dual duct system combines hot and cold air with different volume combinations. They may include single duct VAV terminals connected to the cold medium distribution system for internal cooling only areas, and the cold conduit can be connected to the hot one to serve the perimeter spaces. In this way, is possible to save more heat energy of the air in all those cooling zones, because the temperature is controlled by acting on the volume of the air flow and not on the level of the supply temperature itself (Grendzik, 2007).

The dual-duct air terminals have two terminal cushioning operators: one that makes the unit work as a single-channel VAV terminal block, and a single-channel VAV heating clamp plugged into a physical terminal package. This allows to have greater control and synchronization of the large quantity of the air transported by the system. Using a minimum flow is also a method for having good control, as well as saving the fan's energy.

In this type of system, the VAV configuration has the problem of humidity control during the cooling period. Moreover, for the VAV and for the constant volume system, it is possible to have only one fan or two. The use of only one fan was very popular during the years 80 and 90.

The fan is controlled by two static pressure regulators, one in the hot half and the other in the cold. In the double fan system, the air volume of each duct is independently regulated by the static pressure that is inside the respective duct. Each fan is so dimensioned according to the range and the physical characteristics of the air that must circulate inside the duct (Grendzik, 2007).

2.4.2 ALL-WATER SYSTEM

In an all-water system, the medium used to heat or cool the spaces is water or a cooler. The heat exchange between the water and space is climatized through the process of natural or forced convection. The only exception is for radiant panels, whose heat transfer is purely nominal and depends on its size and position within the room.

These systems can be used for both the heating and cooling periods. In this case, a piping network is designed to distribute hot or cold water to the areas. The radiant panels used for cooling are not the same as those used for industrial processes, because they require a dehumidified air feeder to avoid the formation of condensation in the chamber. These systems can be chosen and installed based mainly on three specific things:

- When there is little space of action than from an energetic point of view. Water is a very efficient means of transporting energy, and there are various types of distribution systems based on when space can be available
- When the air circulation is discouraged for reasons of bad smell or hygienic
- The initial cost of the system is normally less than that of other types of systems

In the past, this type of system was installed in different commercial buildings, residential, office, school, and hospitals, because it adapts very well to any perimeter space.

They are not optimal choices in those situations where there is a good level of ventilation control (internal air quality) and a relative level of humidity is required. For this reason, air handling can be provided by another outdoor unit to maintain good levels of indoor air quality. Nevertheless, they give good control of the environmental temperature. Moreover, the pipes where the water circulates, occupy much less space than the air ducts and use much less energy for the circulation of the water. Nowadays, however, there are a wide variety of proposals in the market and in some cases, other types of systems are more suitable for specific situations, e.g. for schools and offices, is preferable to install a VAV system. For this reason, all water systems are less used and have more specific or limited applications. It offers a wide range of delivery devices, including three types of radiators: a unit, floor and skirting board or convectors.

All-water systems can be classified essentially into three types (Gheji, 2016):

- Two-pipe systems, one pipe for supply and one for return water. Cold or hot water according to the periods of the year flows through a single circuit closed by terminals
- Three-pipe systems, two delivery pipes (one for hot water and the other for cold) and one single for the return
- Four-pipe system, basically a double two-pipe system separate one for hot water and one for cold so as to separate the coils into the terminal units

TWO-PIPE SYSTEM

With a two-pipe system, cooling and heating cannot be distributed simultaneously. One tube is dedicated to the supply, the other is the pipe for the return of the water to the central system. Each terminal is connected then to a delivery pipe and one return (Figure 5). During cooling, cold water flows into the terminals and cooling is obtained both sensitive and latent. During the heating, only the sensitive heat is exchanged.

The temperature level is controlled and regulated directly by the terminal, the flow and flow of the water can be adjusted through the control valve (Gheji, 2016).

Spaces with the same heating or cooling requirements can be grouped in a single area. Then, the design of a circulation and control system is needed in different areas where heating and cooling can be operated separately. This requires a very accurate design and layout since there are only have two tubes available.

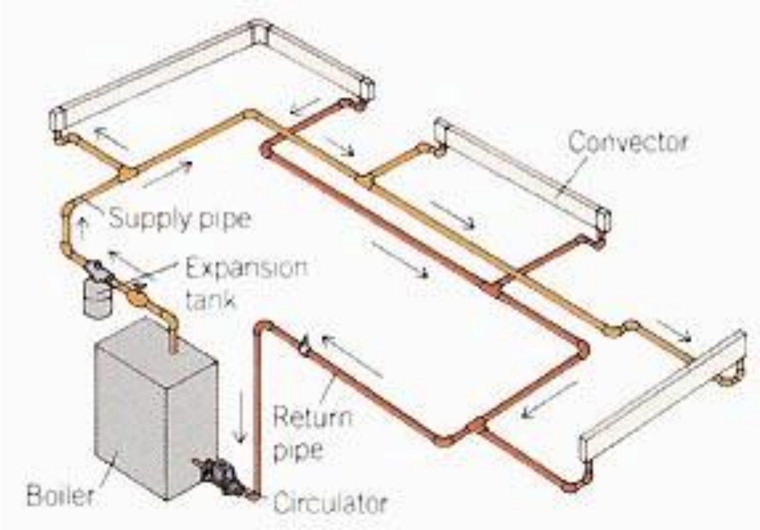


Figure 5: Two pipa all-water HVAC system configuration *(fraserengineering.com)*

THREE-PIPE SYSTEM

Three-pipe systems have two separate pipes: one dedicated to the hot water and one only for cold water, and a single piping for the return. To control the terminal, a three-way valve is used, allowing to determine which flow of water must run through the radiator without the two streams mixing together. This valve is designed to concede the hot spring to open, flow, and be completely closed, equally for the cold door (ARSHAE, 2012).

This plant was often used for the perimeter spaces of large buildings to avoid the many problems of commutation of two-pipe systems. However, they have been slowly replaced by four-pipe installations, more suitable in many solutions. But, in other cases they are still considered the optimum choice despite a are pipe return provides many energy wastes.

FOUR-PIPE SYSTEM

This system is basically comprised of two independent distribution systems: one dedicated only to hot water and the other to chilled water, allowing to have the option of heating and cooling throughout the year.

Each terminal comes with two coils, two water flow control valves and two pipes for the return. The two valves can be controlled by the room thermostat, indicating the level of degrees you want. Within this system, are eliminated the costs for complex zoning, since in each environment can be chosen whether heating or cooling, since the whole system has two separate pipes to satisfy one or the other requirement (Gheji, 2016).

Usually, to save energy is possible to suspend the circulation of cold water in winter and vice versa the hot water in the summer, and some systems have precisely incorporated this mode of seasonal switching. In spring and autumn, both modes of operation of the system are available.

2.4.3 AIR-WATER SYSTEM

The water-and-air systems serve both air conditioning and water areas, directly from the terminal units.

This system includes components for centralized air-conditioning, including induction units, fan coils, or the normal vents, together with water distribution components through ducts and terminal units in the rooms, such as radiant panels. The water and air are brought to the conditions chosen by the occupants in a room used with all the necessary mechanical equipment. This system can be called hybrid because it incorporates many of the features of all-air and all-water approaches into one plant (Ross, 2004).

The cross-section of the tubing is less than that of the ducts because the specific heat and the density of the water are greater than those of the air and with this foresight, it is possible to provide an equal cooling or heating capacity to the environments.

In these plants, most of the work is made by the water, so it is possible to install smaller diameter ducts than those used in all-air systems, requiring lower spaces dedicated to the system. In case the system is conceived with the primary air system (i.e. power supply) of the same capacity of the ventilation requirement, or to equally balance the discharge requirements, it is possible to eliminate the component of the return.

It is possible to control the system in such a way that it only functions by water, temporarily shutting off the central ventilation part. Normally, the primary air system is designed in such a way that it works at constant volume and can usually be comparable to the single zone. The water distribution plant component can be a two, three-or four-pipe arrangement as for all-water systems.

The weak point of these plants is its operation during the intermediate seasons. It is quite complicated to control the humidity levels compared to all-air systems because it depends exclusively on the ambient temperature.

For this reason, it is more suitable for perimeter construction spaces where there are highly sensitive loads where the control of humidity levels is not fundamental. But to have a minimum control of the humidity levels it is possible to install a separate heating coil in order to allow correct dehumidification and avoid overheating. Therefore, the use of four tubes is almost always the optimum choice, and although it is the most expensive, is also the most efficient.

The primary air is cooled and brought to the desired temperature using chilled water, and thanks to the aid of a cooler and an optional heating coil, can also be inserted for operation in the winter period. In each zone, a device for the individual temperature control is foreseen.

2.5 LIFE-CYCLE COSTING OF HVAC SYSTEMS

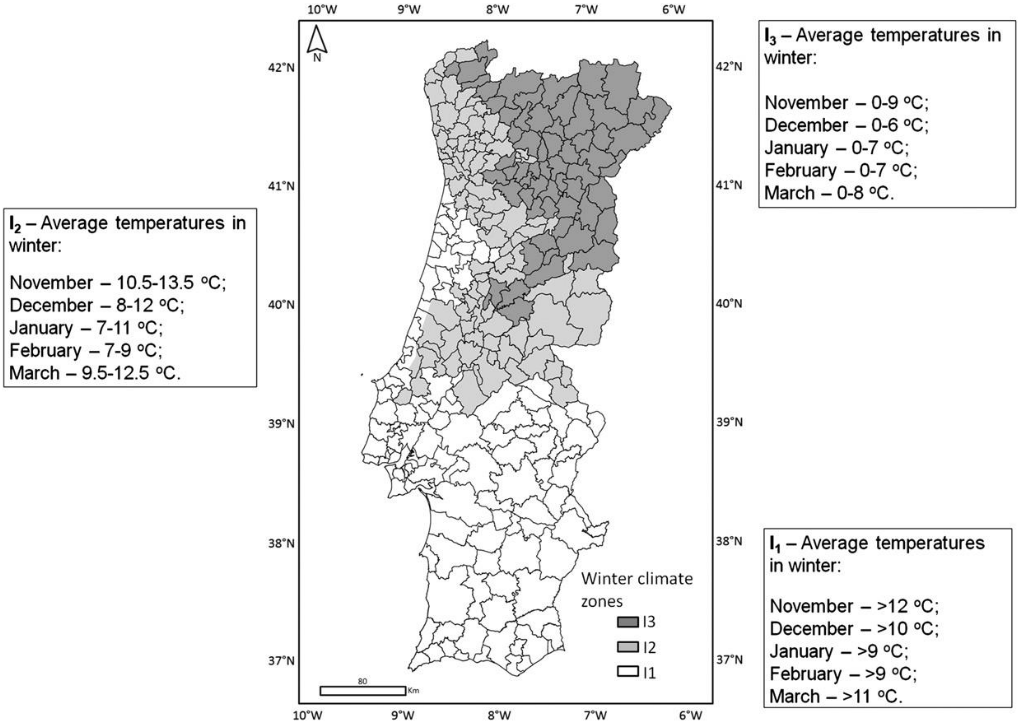
The technique adopted for the HVAC life-cycle cost analysis in this Thesis is presented in the Directive 2014/24/EU (SPP Regions, 2017). This method enables planners and engineers, and facilities to conduct economic analyzes and evaluate design decisions before construction or extensive design. The method will be discussed in detail in the Chapter 3.3.1.

(Griffith et al., 2007) develops a methodology for modelling the energy performance of commercial buildings located in various American cities with different climate. It has been shown that the structure of the building and weather affects the energy consumption. The paper reports a variation in the HVAC energy consumption from 16 kWh/m2 yr to almost 79 kWh/m2 yr according to the characteristics of the building and the site. (Lecamwasam et al., 2012) shows that, in the typical energy consumption for an office building, generally the HVAC system accounts approximately for 40% of total. (Boyano et al., 2013) exposes a study on energy demands and potential savings in office buildings in major European cities, notably Tallinn, Madrid and London. Specifically, it follows that the energy consumption of the HVAC system in the office located in Madrid is about 30 kWh/m2 yr and Tallinn in estimated 60 kWh/m2 yr.

3 CASE STUDY AND METHODOLOGY

3.1 CLIMATE IN PORTUGAL

Portugal is a western European country, overlooking the Atlantic Ocean to the south and west and bordered on the north and east by Spain. Base on the typical range of recorded temperatures, mainland Portugal was divided in three different climatic regions for heating (Summer) and cooling (Winter) seasons. The regions are rated from I1 (Winter) / V1 (Summer) to I3 (Winter) / V3 (Summer) from the milder to more extreme climates. In total, there are 9 possible combinations of heating and cooling conditions throughout the Portuguese mainland territory. From Figures 6 and 7, is possible to distinguish between the three different climatic zones and the respective average temperatures. The climatic zones are not the same in winter and in summer, as they change every season, influenced by the altitude and the proximity of the sea. In addition, Gulf Stream impact significantly the Portuguese climate.



I_3 – Average temperatures in winter:

November – 0-9 °C;
December – 0-6 °C;
January – 0-7 °C;
February – 0-7 °C;
March – 0-8 °C.

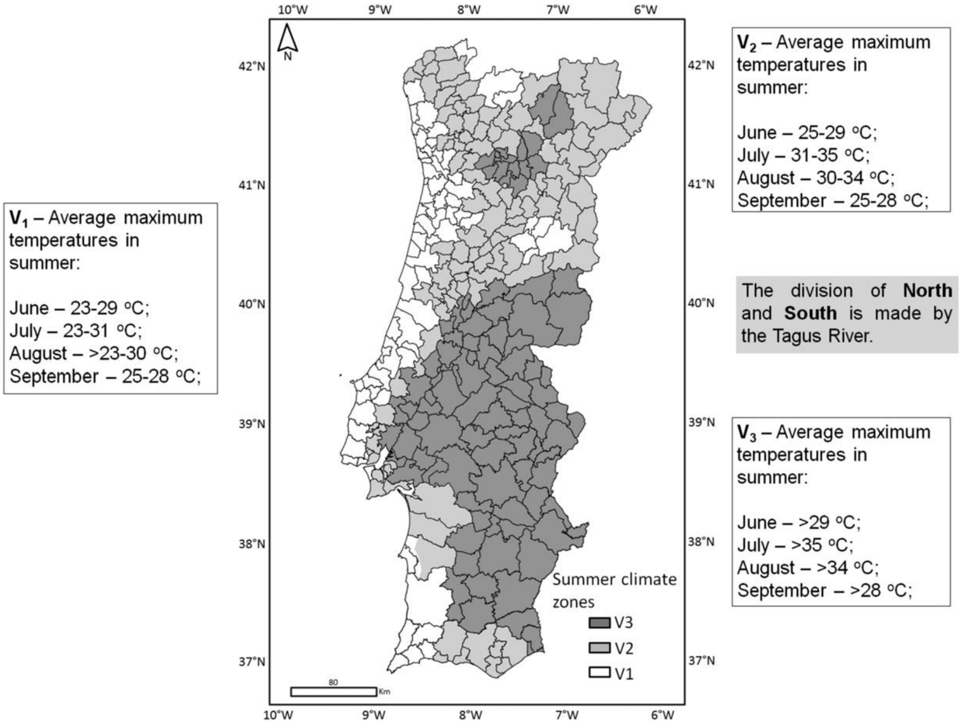
I_2 – Average temperatures in winter:

November – 10.5-13.5 °C;
December – 8-12 °C;
January – 7-11 °C;
February – 7-9 °C;
March – 9.5-12.5 °C.

I_1 – Average temperatures in winter:

November – >12 °C;
December – >10 °C;
January – >9 °C;
February – >9 °C;
March – >11 °C.

Figure 6: Portuguese winter climate zones *(Ferreira & Pinheiro, 2011)*



V_1 – Average maximum temperatures in summer:

June – 23-29 °C;
July – 23-31 °C;
August – >23-30 °C;
September – 25-28 °C;

V_2 – Average maximum temperatures in summer:

June – 25-29 °C;
July – 31-35 °C;
August – 30-34 °C;
September – 25-28 °C;

The division of **North** and **South** is made by the Tagus River.

V_3 – Average maximum temperatures in summer:

June – >29 °C;
July – >35 °C;
August – >34 °C;
September – >28 °C;

Figure 7: Portuguese summer climate *zones (Ferreira & Pinheiro, 2011)*

Despite the division, Portugal has a relatively mild climate, with limited regions with extremely hot or cold seasons compared to other regions of the globe. Still, for the sake to the occupants' comfort, buildings on the Portuguese territory require heating and cooling systems. There are areas where high temperatures are reached during the summer season (for example the average maximum temperature in summer in Evora reach 30.2 °C and in Beja reach 32.6 °C, according to the Portuguese Meteorology Institute) (Ferreira & Pinheiro, 2011), and, in other regions during winter temperatures reach below 0 °C.

In order to design energy efficient buildings, it is indispensable to know the climatic conditions of the location in which the project will be executed. This is the key requirement to implement the adequate solution to minimize the LCC associated to heating and cooling the building. However, the energy consumption does not depend on the average temperature but on the effective temperature pattern. For instance, 10 very hot days followed by 10 cold days will not result in the same energy consumption of 20 days with the same average temperature. Therefore, there will be a difference between the estimate and effective energy consumption of the buildings. The magnitude of the difference will depend on various factors, some related to the climate (temperature pattern), others to the building (thermal inertia) or even to the building use and users (type of activity, cloths used).

3.2 CASE STUDY

The office buildings studied were selected from locations covering the most relevant climatic conditions of Portugal mainland were the majority of the population is located. As such, the majority of the buildings are located in the west cost north of Lisbon (Figure 8).

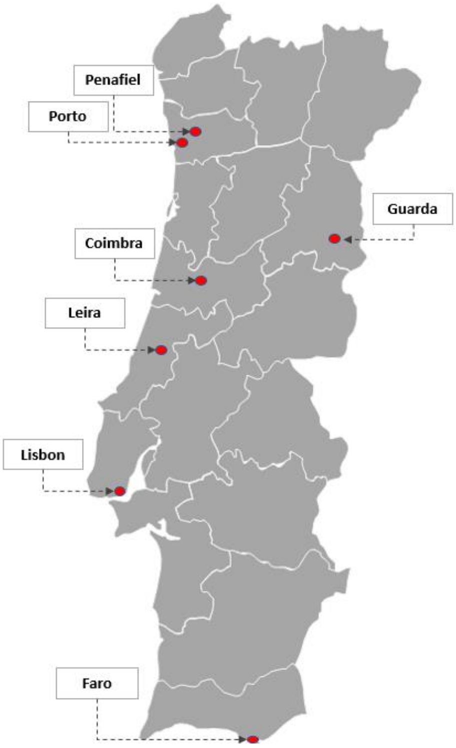


Figure 8: General overview map

This closeness to the sea and the influence of the Gulf Stream means that in the winter season, the climate is mild and temperatures below 9 °C are almost never reached during the day. It will be shown later, during the data analysis, that, with this type of climate in winter, the buildings need low power heating systems. On the contrary, during the warmer seasons, all the Portuguese territory is characterized by having very high temperatures, being necessary to install high power cooling systems that more energy than in winter.

3.2.1 PENAFIEL

The office building further north is located in Penafiel. The building is located in Lugar da Bujanda in the district of Penafiel, in the province of Porto, on the outskirts of an urban centre. The climatic zone is I2-V2, the distance to the sea is of about 40 km and the altitude 223 m. Figure 9 presents an aerial view of the building and Figure 10 a front view.

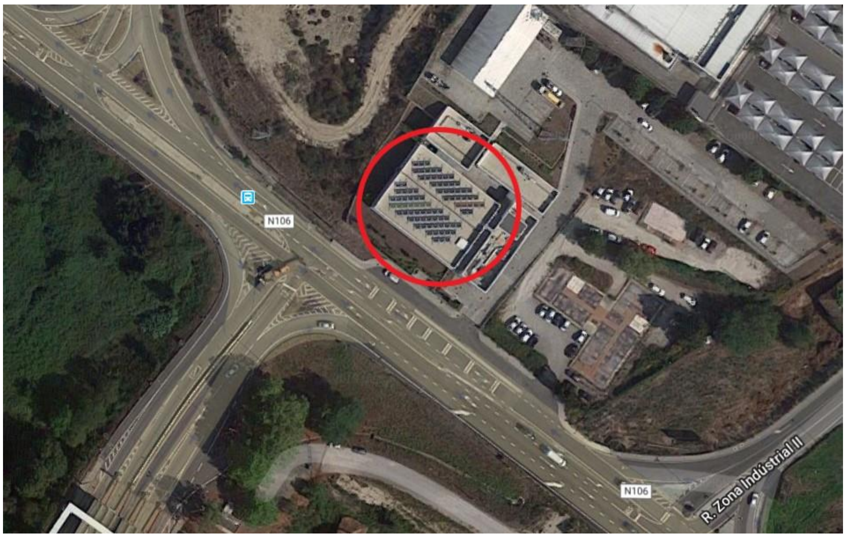


Figure 9: Penafiel's office map *(Google Earth)*

Figure 10: Penafiel's office building

The building, built in 2011, has two floors (ground floor and first floor), with a useful area of 1590.30m^2 occupied mainly with offices. The building is made up of the following spaces: hall, secretarial office, corridors, offices, archives, multipurpose rooms, refectory, sanitary area, and technical room. The structure's layout is rectangular in shape and the facades of the building are north-east, northwest, southeast, and south-west. The roof is of the flat type where solar panels are arranged to produce domestic hot water and photovoltaic panels that contributes to the heating in the winter months. Table 1 shows the transmittance values of the main structures in contact with the external environment of opaque elements and transparent elements (energy certificate, 2016).

Table 1: Penafiel building's transmittance values of opaque and transparent elements

Description of the item	Thickness (m)	Area (m^2)	U ($W/m^2C°$)
External Wall in masonry, covered on both sides with plaster	0.38	406.90	0.96
Wall in contact with the ground, masonry, covered on both sides with plaster	0.28	31.90	1.50
External horizontal Cover, heavy construction and with inner lining in plasterboard	0.38	915.70	2.60
Floor in contact with the ground with ceramic flooring	0.45	355.60	1.00
Floor in contact with unheated space with ceramic flooring	0.40	586.40	2.21
Double-glazed Windows with metallic frame without thermal cut		203.70	3.90

During the design, it has been decided to install the split HVAC system type VRF. With the variable refrigerant flow (VRF) systems it is possible to vary the refrigerant flow to the internal units, to achieve comfort for the occupants. A VRF system can be used both for heating during the colder months and for the conditioning of summer periods. Table 2 lists the characteristics of the systems currently in use (Company´s energy certificate, 2016).

Table 2: Penafiel building's HVAC system characteristics

Model	Quantity	Unitary Heating capacity(kW)	COP (%)	Unitary Coopling capacity (kW)	EER (%)
Toshiba MMY-MAP0802FT8	2	25	3.97	22.4	3.69
VRF Toshiba	1	94.5	3.61	84	3.28

In addition, 20 kW of solar panels are installed, used for winter heating. For the ventilation system, 3 new air treatment units are used for a total flow of new air of 9300 m^3/h.

3.2.2 PORTO

In Porto, there are two buildings inaugurated in 2011. Figure 11 presents an aerial view of both, with bottom one designated as Building A and the upper as Building B. The two buildings are located within the urban area of Porto on Avenida Ophelia Diogo da Costa 77. They are in the climatic zone I1-V2 at an altitude of about 86m, distant less than 5 km from the sea. A front view of building A is presented in Figure 12.

Figure 11: Porto's offices map *(Google Earth)*

Figure 12: Porto A's office building

It is one of the largest properties analysed in this thesis, with a total area of 18,654.47 m2. The building is rectangular in shape and is placed on ten floors, three of which are underground in which there are parking spaces and is located in the area of technical premises and sanitary installations. In the first underground floor, there are a laboratory, a reprography, meeting rooms, sanitary facilities, and an auditorium. In the ground floor, there is a shop, a medical studio, a reception, a meeting room, and a cafeteria. The remaining floors are mainly used for offices and meeting rooms. Table 3 reports the values of transmittance of opaque and transparent elements in contact with the external environment (Company´s energy certificate, 2016).

Table 3: Porto Building A's transmittance values of opaque and transparent elements

Description of the item	Thickness (m)	Area (m²)	U (W/m²C°)
External wall, double masonry, with external thermal insulation	0.38	1532.70	0.66
External Wall of the South ground floor in contact with the ground, in double masonry, with insulation	0.36	31.60	0.72
Horizontal outer Cover of the sixth floor	0.58	986.50	0.58
Floor in contact with unheated space	0.75	1270.9	0.58
Double glass Windows with metallic frame		4.9	3.90
Double-glazed ground-floor Windows with fixed sheet metal frame, without thermal cut		856.6	6.00
Windows of the upper floors with double glazing with metal frame, with thermal cut		2224	3.30

To heat and cool this building, it was chosen an HVAC system of the air-cooled chiller type. This is one of the most widely used systems, thanks to its great flexibility in adapting to any kind of need (on small to large applications), having a wide variety of system types available. The air-cooled chillers currently in use in the building are listed in the Table 4 (Company´s energy certificate, 2016).

Table 4: Porto Building A's HVAC system characteristics

Model	Quantity	Unitary Heating capacity(kW)	COP (%)	Unitary Coopling capacity (kW)	EER (%)
Daikin EWYD360AJYNN-Q	1	274	3.06		
Daikin EWYD190AJNVT	2			184	2.3
Daikin EWAD 340AJNVT-QE	1			321	2.6

Moreover, on the roof of the building are installed 82.5 kW of photovoltaic panels that contribute to the conditioning during the hottest months of the year. A total power of 771.5 kW for air conditioning and only 274 KW for heating, being the city´s climate heavily influenced by the Gulf Stream as it is near to the Atlantic Ocean.

For the ventilation system, it is used two VRV branded Daikin, the models are VAM 500 and VAM1500.

Building B (Figure 13) has similar constructive characteristics of Building A because they were designed and built together. It Is also a large property, having an area of 14,850.52 m2. It is composed of ten floors, three of which are underground used for parking with technical premises. On the ground floor, there is a restaurant, a gym and a service space. The remaining floors are dedicated to the offices.

Figure 13: Porto B's office building

Table 5 shows the transmittance values of the main structures in contact with the external environment of opaque elements and transparent elements (energy certificate, 2016).

Table 5: Porto Building B's transmittance values of opaque and transparent elements

Description of the item	Thickness (m)	Area (m^2)	U ($W/m^2C°$)
External Wall, double masonry, with external thermal insulation	0.38	1174.5	0.66
Horizontal outer Cover of the sixth floor	0.58	930.40	0.58
Floor in contact with unheated space	0.75	276.8	0.58
Double-glazed ground-floor Windows with fixed sheet metal frame, without thermal cut		343	6.00
Windows of the upper floors with double glazing with metal frame, with thermal cut		1794.7	3.30

Being that Building A and Building B were designed as a unique project, they were chosen for both buildings of the air-cooled chiller HVAC. The air-cooled chillers installed are listed in the following table (energy certificate, 2016).

Table 6: Porto Building B's HVAC system characteristics

Model	Quantity	Unitary Heating capacity(kW)	COP (%)	Unitary Coopling capacity (kW)	EER (%)
Daikin EQYD 320DZ-SL003	1	334	2.8	315	2.75
Daikin EWAD 210E-SL002	2			208	2.86

For the ventilation system, there are two UTAs Wesper PR @ 200 and a VRV Daikin VAM 650.

3.2.3 GUARDA

The building in Guarda is located in Rua Estrada Nacional 16, Quinta d'el Rei a Guarda. It was built in 2011 on the outskirts of an urban area. Guarda is in the climate zone I3-V2, at an altitude of 958 m, at more than 5 km from the sea. An aerial and a front view of the building are presented in Figures 14 and 15, respectively.

Figure 14: Guarda's office map *(Google Earth)*

Figure 15: Guarda's office building

It is a service building intended for office use on two floors, with a useful floor area of 1079 m^2. The Building is of a rectangular shape with flat roof in which are installed solar thermal panels for the production of domestic hot water. The values of transmittance of opaque elements and transparent elements are reported on Table 7 (Company´s energy certificate, 2016).

Table 7: Guarda building's transmittance values of opaque and transparent elements

Description of the item	Thickness (m)	Area (m^2)	U ($W/m^2C°$)
External Wall, with insulation in fibre cement	0.38	262.1	0.45
External Wall, with insulation in extruded polystyrene foam	0.35	195	0.44
External Cover	0.58	698.7	0.46
Foundation Floor	0.75	698.7	0.55
Double-glazed Windows with fixed sheet metal frame, with thermal cut		142	2.60

In the building are currently installed VRF HVAC system and split. The Table 8 lists the features of the building's HVAC systems (Company´s energy certificate, 2016).

Table 8: Guarda building's HVAC system characteristics

Model	Quantity	Unitary Heating capacity(kW)	COP (%)	Unitary Coopling capacity (kW)	EER (%)
Toshiba MMY-MAP0802FT8	1	25	3.97	22.4	3.69
Toshiba MMY-MAP1002FT8-E	1	31.5	3.61	28	3.41

3.2.4 COIMBRA

The structure is situated on the outskirts of Coimbra, in Avenida Urbano Duarte, in the climatic zone I1-V2, at an altitude of 29 m and at a distance from the maritime coast more than 5 Km. Figure 16 and 17 presents respectively an aerial and a front view of the building.

Figure 16: Coimbra's office map *(Google Earth)*

Figure 17: Coimbra's office building

The property, built in 2008, has the dominant use of office, with a total area of 10,390.82 m2 and is classified as a large service building. It consists of seven floors, two of which are underground. In these, there are parking lots and a technical area. On floor 0 there are other car parks, an auditorium, a technical room, and a bar. The remaining floors are mainly for offices. Moreover, on the roof of the building is installed a photovoltaic system for the production of electricity consumed by the building. Table 9 shows the main transmittance values (Company´s energy certificate, 2016).

Table 9: Coimbra building’s transmittance values of opaque and transparent elements

Description of the item	Thickness (m)	Area (m^2)	U ($W/m^2C°$)
External Wall	0.36	1810.9	0.96
Underground Wall	0.29	1297.7	1.16
External horizontal Cover	0.48	1432.2	2.6
Floor in contact with an unheated space	0.45	1325.9	2.21
Double glass Windows with metallic frame, with thermal cut		123.5	3.90
Windows of the upper tops with double glass with metallic frame, with thermal cut		602	3.70

The Air-conditioning is centralized with an HVAC system unit of the air-cooled chiller type with four tubes. The main characteristics of the plant are described in Table 10 (Company´s energy certificate, 2016).

Table 10: Coimbra building’s HVAC system characteristics

Model	Quantity	Unitary Heating capacity(kW)	COP (%)	Unitary Coopling capacity (kW)	EER (%)
Trane GW-1335-G0	1	137	2.98	120	2.45

In addition, 72 modules of photovoltaic panels installed on the roof of the building are also used for the summer air-conditioning. The ventilation system consists of four UTA's brand GEA models ATP 25, 20AVBV, ATP 20, 20AVBV and two ATP 20,15/VBV.

3.2.5 LEIRIA

The building in Leiria is one the newest buildings analysed, being inaugurated in 2016. The building is located in Rua São Luis, in the residential area of Leiria. It is covered in the climatic zone I1-V2, at an altitude of 100 m. Figure 18 presents an aerial view of the building and Figure 19 a front view.

Figure 18: Leiria's office map *(Google Earth)*

Figure 19: Leiria's office building

The 1100.80 m2 structure was built in a lot of hilly terrain, with an altitude difference of 3.44 m from one end of the construction to the other. The edifice was designed and conceived to be used as an office, rectangular in shape and on two floors: one above ground and one basement. The production of domestic hot water is made by a solar thermal system. Table 11 details the transmittance values of the main construction elements of the building (Company´s energy certificate, 2016).

Table 11: Leiria building’s transmittance values of opaque and transparent elements

Description of the item	Thickness (m)	Area (m^2)	U ($W/m^2C°$)
External Wall	0.37	275.3	0.53
External horizontal Cover	0.49	771.3	0.58
Floor in contact with the outside	0.45	397.5	0.66
Windows of the upper tops with double glass with metallic frame, with thermal cut		613	1.5

As for heating and air conditioning system, it was decided to opt for VRF. The Table 12 lists the characteristics of the systems currently in use (Company´s energy certificate, 2016).

Table 12: Leiria building’s HVAC system characteristics

Tipology	Quantity	Heating capacity(kW)	COP (%)	Coopling capacity (kW)	EER (%)
VRF	1	100	3.7	90	3.4
VRF	1	28	3.8	31.5	4.3
VRF	1	15.3	3.3	18	2.8

3.2.6 LISBON

There are three buildings to analyse in Lisbon. Building A at Avenida 24 de Julho, Building B at Avenida José Malhoa and finally Building C the office of Rua Camilo Castelo Branco. Lisbon is in the climatic zone I1-V3 at a distance of about 15 km from the maritime coast. The Figure 20, 21 and 22 present an aerial view of the tree buildings.

Figure 20: Lisbon Building A ’s office map *(Google Earth)*

Figure 21: Lisbon Building B ’s office map *(Google Earth)*

Figure 22: Lisbon Building C ’s office map *(Google Earth)*

With its 39,122.02 m2 of surface, Building A the largest building object of this study. Along with Leiria´s building it is one of the newest buildings analysed, also inaugurated in 2016.

Figure 23: Lisbon Building A's office building

It is possible to see in Fig. 23 that, the construction is made up of two eight-floor buildings, joined together by two walk ways and seven underground floors. In the floors from 1 to 7, there are the work areas (mainly offices), on floors 0, -1 and-2 are present: gym, shopping area, restaurant, and auditorium. The remaining floors are dedicated to the technical area and parking. The building has a solar thermal system for the production of domestic hot water, and a photovoltaic plant of 353 modules. The transmittance values of the main opaque and transparent structures are reported in Table 13 (Company´s energy certificate, 2016).

Table 13: Lisbon Building A 's transmittance values of opaque and transparent elements

Description of the item	Thickness (m)	Area (m^2)	U ($W/m^2C°$)
External Wall	0.59	263.2	0.31
External Wall	0.38	139.2	0.52
Underground Wall	0.42	212.4	0.18
Underground Wall	1.44	2489	0.25
External horizontal Cover	0.50	3413	0.39
Floor in contact with the outside	2.00	3413	0.17
Windows of the upper tops with double glass with metallic frame, with thermal cut		12,257	2.41

To achieve optimum comfort conditions, the offices have installed four chillers with very high-power brand Climaveneta. In Table 14, it is possible to see the main features of HVAC systems (Company´s energy certificate, 2016).

Table 14: Lisbon Building A 's HVAC system characteristics

Model	Quantity	Unitary Heating capacity(kW)	COP (%)	Unitary Coopling capacity (kW)	EER (%)
Climaveneta NECS/B1614	2			411.7	2.7
Climaveneta NECS-Q/B1614	2	447	3.45	412	2.7

Building B (Figure 24) built in 2004, is located in the urban area of Lisbon and has a total area of 10,550 m2. The building rises for eleven floors where the intended use is that of office and the main facade is oriented towards the northeast.

Figure 24: Lisbon Building B's office building

The listing of the characteristics of opaque and transparent structures are presented in Table 15 (Company´s energy certificate, 2016).

Table 15: Lisbon Building B ’s transmittance values of opaque and transparent elements

Description of the item	Thickness (m)	Area (m^2)	U ($W/m^2C°$)
External Wall	0.55	2180	0.59
External horizontal Cover	0.45	1209	3.51
Foundation Floor	0.45	1231	3.1
Windows of the upper tops with double glass with metallic frame, with thermal cut		1219.4	3.5

The Air conditioning is centralized with two chiller units. The main features of the HVAC system are described in the Table 16 (Company´s energy certificate, 2016).

Table 16: Lisbon Building B ’s HVAC system characteristics

Model	Quantity	Unitary Heating capacity(kW)	COP (%)	Unitary Coopling capacity (kW)	EER (%)
Climaveneta SME 1202	1			335	2.23
Climaveneta HPAN/SL 1004	1	266	2.4	240	2.66

Building C (Figure 25) inaugurated in 2008 has an area of 8,602.7 m2, of which 5,863.7 m2 of offices and 2.739 m2 of parking.

Figure 25: Lisbon Building C’s office building

The building has thirteen floors, and as mentioned before it is used primarily as an office. The transmittance values of the main opaque and transparent structures are reported in Table 17 (Company´s energy certificate, 2016).

Table 17: Lisbon Building C ’s transmittance values of opaque and transparent elements

Description of the item	Thickness (m)	Area (m^2)	U ($W/m^2C°$)
External Wall	0.29	887.9	1.3
External Wall	0.20	262.9	1.7
Underground Wall	0.40	14.5	0.8
Underground Wall	0.35	64.5	1.5
External horizontal Cover	0.50	841.5	2.6
Foundation Floor	0.50	842.8	2.21
Windows of the upper tops with double glass with metallic frame, with thermal cut		728.8	3.9

Three chillers are installed As HVAC system. The air-cooled chillers installed are listed in Table 18 (Company´s energy certificate, 2016).

Table 18: Lisbon Building C 's HVAC system characteristics

Model	Quantity	Unitary Heating capacity(KW)	COP (%)	Unitary Coopling capacity (KW)	EER (%)
Daikin EUWY N070CZ6YL	2	167.4	2.35	165.8	2.31
Daikin EWYQ 180DAYNN	1	199	2.87	183	2.93

3.2.7 FARO

The building is in the outskirts of Faro, in the climatic zone I1-V3, at a distance of 6 Km from the sea and at 10 m of altitude.

Figure 26: Faro's office map *(Google Earth)*

Figure 27: Faro's office building

It Is a building mainly used as an office and has an area of 3,519.5 m2 built in 2011. The main facade is facing north, and it is composed of five floors, in which the ground floor is the hall, offices, bar, meeting room; On the upper floors, there are mainly offices. There are also parking spaces in the basement. The Table 19 shows a brief description of opaque and transparent structures in contact with the external environment (Company´s energy certificate, 2016).

Table 19: Faro building 's transmittance values of opaque and transparent elements

Description of the item	Thickness (m)	Area (m^2)	U ($W/m^2C°$)
External Wall	0.3	1910	1.1
External horizontal Cover	0.3	1447	2.6
Windows of the upper tops with double glass with metallic frame, without thermal cut		487.3	3.6

The selected HVAC systems are chiller type. The Table 20 lists the systems currently used by the building (Company´s energy certificate, 2016).

Table 20: Faro building 's HVAC system characteristics

Model	Quantity	Unitary Heating capacity(kW)	COP (%)	Unitary Coopling capacity (kW)	EER (%)
Daikin EWYD 130DAYN	1	149	3	136	2.9
Daikin EWYD 100DAYN	1	114	3	100	2.9

3.2.8 SUMMARY DATA ANALYSIS

Two of the offices studied in this thesis (Leiria and Lisbon Building A) have an HVAC system installed in 2016, and thus, given their short operation life, they are considered new and high efficient; therefore, it is not necessary or recommended to replace them. So, they will not be included in the analysis.

Table 21 shows a summary data analysis collected from the company's energy certificates of 2016.

Table 21: Summary data analysis

Location	Office	Est. Building years	Area (m2)	Brand and Type of HVAC System	Est. HVAC system installed years	Annual energy consumption (kWh/m2year)
Penafiel	Penafiel	2011	1,590	VRF Toshiba	2011	24.66
Porto	Porto Building A	2011	18,654	Chiller Daikin	2011	37.05
	Porto Building B	2011	14,850	Chiller Daikin	2011	88.17
Guarda	Guarda	2011	1,079	VRF Toshiba	2011	18.14
Coimbra	Coimbra	2008	10,390	Chiller Daikin	2008	30.55
Lisbon	Lisbon Building B	2004	10,550	Chiller Climaveneta	2004	17.04
	Lisbon Building C	2008	8,602	Chiller Daikin	2008	39.98
Faro	Faro	2011	3,519	Chiller Daikin	2011	11.83

3.3 METHODOLOGY

3.3.1 LIFE-CYCLE COST ANALYSIS

The Life-Cycle Cost Analysis (LCCA) is a method to estimate the overall cost during all the life of the project. It considers the purchase expense and operating costs. All the costs must be referred at the same time that is normally the present, for this reason, the overall future operating costs are discounted to the time of purchase and summed. The technique adopted for the HVAC life-cycle cost analysis in this Thesis is presented in the Directive 2014/24/EU.

The LCCA should be executed during the project phase and includes different alternatives. Usually, the choices are similar because fulfill the same performance requirements, but they have different initial and operating costs. With the LCCA it is possible to compare and select the one that maximizes the net savings.

The standard Life-cycle cost formula is described by the equation (3.1) (Rosenquist et al., 2004):

$$LCC = IC_0 + \sum_{n=1}^{N} \frac{O\&M_n}{(1+r)^n} + \frac{SV}{(1+r)^t} \quad (3.1)$$

Where:

LCC - life-cycle cost (€)

IC_0 - total installed cost at year zero (€)

$O\&M_n$ - operating and maintenance cost at year n (€)

r - discount rate (%)

n - year for which operating cost is being determined

t - year end of the project´s lifetime

During the lifetime of any type of project, the costs can be stored in two main categories: initial expenses and future expenses.

INITIAL INVESTMENT

The initial investments can be defined as the costs that are made before the project begins to operate.

In the case of an HVAC system, the initial expenses or CAPEX are defined by the sum of two main costs: equipment and installation. The equipment cost is made by the sum of every single component of an HVAC system price (chiller, ducts, valves, split, etc.). The installation expense represents all the costs required to install all the system in loco, including labour, overhead, and any miscellaneous materials and parts.

FUTURE OPERATION COSTS

The future operation expenses are all the costs incurred after the installation or construction of the facility; all the costs involved during the lifetime of the project.

The operation costs of an HVAC system are obtained by the sum of the energy, ordinary and extraordinary maintenance costs (3.2) (Rosenquist et al., 2004).

$$O\&M = EC + MC + RC \tag{3.2}$$

Where:

O&M - operating and maintenance cost (€)
EC - energy cost (€)
MC - maintenance cost (€)
RC - repair cost (€)

These types of expenses are typically estimated yearly, relying primarily on future previsions by assumptions.

Energy costs

The annual energy cost is computed by calculating in according with the formula (3.3):

$$EC = E_a \times P_{elec} \tag{3.3}$$

Where:

EC - energy cost (€)
E_a - annual energy consumption (kWh)
P_{elec} - electricity price (€/kWh)

Is to be noted that, the energy consumptions can be difficult to predict precisely in the design phase of the project. Moreover, may be taken into consideration all the factors that have a strong impact in the energy consumption, like location, temperature profile, building’s type, area, materials used in the during the construction, occupancy rates, etc. Finally, in the LCCA calculation must be considered the variation of the electricity price in the future depending on the inflation rate.

Maintenance costs

Maintenance costs are occurred to allow construction systems to function properly during their useful life. Firstly, it is possible to make a primary distinction in two main types of maintenance: ordinary and extraordinary.

Routine maintenance is used to control the proper operation of the system and to prevent future breakage and heavy charges for repairs. This can also be called preventive, and it is customary to do programming of all the various maintenance planned for the various elements of the system.

The HVAC systems are composed of different modules and each one needs its own specific maintenance. Usually, all these maintenances can be planned in the design phase in order to avoid damages and to ensure the optimal performance continuity of the system.

Maintenance is established according to four criteria:

- time
- hours of operation
- productivity
- mixed

Although routine maintenance is performed at the plant, is possible that some components can randomly break or damage, depending on unpredictable events. Thus, it is necessary to consider in the LCC, extraordinary maintenance or repair costs, which are not foreseen in the ordinary maintenance plan.

Although with extraordinary maintenance it is not foreseeable the exact moment of when it must be done, it is good rule to establish possible scenarios in the LCCA and to hypothesize any costs to be incurred in case of breakage or damage of the components of System.

SALVAGE VALUE

When the system is replaced or its lifespan expires, there is the possibility that it has a resale or residual value, being some components possible for recover or reuse.

According to the LCCA convention (State of Alaska – Department of Education & Early Development , 2018), the salvage value is the only component in which it is acceptable to have a negative value, i.e. a reduction in total costs within the formula, which means that there is a possible gain as the system can be sold or reused. On the other side, a positive value occurs when there is a cost in association with the disposal or the demolition of the system and it has to be included in the LCCA. The null value instead means that at the end of the study period the owner will not earn or spend anything.

STUDY PERIOD

One of the fundamental components of the LCCA equation is the study period. It is basically the time period in which all costs, expenses, system gains are estimated and analysed. The study period varies depending on the project to be assessed or depending on the needs of the owner and is approximately the useful life of the system. However, LCCA is Usually calculated over medium to long periods, i.e. 10, 20 or 40 years.

A useful life of 20 years is hypothesized For an HVAC system.

DISCOUNT RATE

The discount rate is another important element at the end of the formula because it is used to compare the costs incurred at different times during the study period with a return from an alternative investment. It represents the minimum return acceptable for the investor (Fuller, 2010).

3.3.2 ASSUMPTIONS FOR THE MODEL

In this thesis, buildings used for real offices, which are located in various parts of Portugal, are studied.

All data from every building described in Chapter 3.2 were extrapolated from the energy certificates updated in 2016. Given that all offices were built after 2000, the main study of this thesis is to run an LCCA on the replacement of the existing plants with a new generation of the same type.

If it is decided to completely change the type of the system already installed to reduce overall energy expense, the cost for the whole substitution would be very high and not necessary. This is because the useful life of the distribution and delivery components is much more durable than that of the source components, which is usually about 20 years old (ARSHAE, 2012). Consequently, it just has to change only the latter.

Two of the offices studied in this thesis (Leiria and Lisbon Building A) have an HVAC system installed in 2016, and thus, given their short operation life, they are considered new and high efficient; therefore, it is not necessary or recommended to replace them. So, they will not be included in the analysis.

Starting to examine each variable from the current year, which by convention of the methodology is the Year Zero, the first costs to be addressed are:

- Equipment purchase: following consultation with commercial agents of Daikin, Toshiba and Climaveneta, new models were selected to replace the installed one. The characteristics of the new models were given from the companies, reflecting un upgrade of the already installed solutions. It is assumed that the payment is all concentrated in Year Zero

- Installation cost: varies according to the size of the system and it is possible to decide and fix it with the installation company. After collecting several estimates from commercial agents of Daikin, Toshiba and Climaveneta, it is possible to assume with a reasonable margin of error that the cost of installation is about 70% of the equipment purchase. It is also assumed that the whole payment occurs in Year Zero
- Residual value: being that all HVAC systems installed in the offices to be investigated are less than 20 years old, it is reasonable to assume that they have a residual value, but given the scarcity of information about the initial purchase price, any residual value from the already installed HVAC models, will be not included in the LCCA

The characteristics of the new models compared to the installed systems are shown in the Table 22.

Table 22: Comparison of the characteristics of the installed and new HVAC systems

Office	Brand	OLD Model	Unitary Heating capacity (kW)	COP	Unitary Cooling capacity (kW)	EER	NEW nodel	Unitary Heating capacity (kW)	COP	Unitary Cooling capacity (kW)	EER
Penafiel	Toshiba	MMY-MAP0802FT8	25	3.97	22.4	3.69	MMY-MAP0806FT8P-E	25	4.14	22.4	3.76
	Toshiba	n.a.	94.5	3.61	84	3.28	MMY-AP3016HT8P-E	95	3.94	85	3.20
Porto Building A	Daikin	EWYD 360AJYNN-Q	274	3.06			N/A				
	Daikin	EWAD 190AJNVT			184	2.3	EWAD190TZ -PL B1			366	3.64
	Daikin	EWAD 340AJNVT-QE			321	2.6	EWYD320-BZSS	334	2.82	323	2.75
Porto Building B	Daikin	EWAD 210E-SL002			208	2.86	EWAD220TZ -PL B1			216	3.56
	Daikin	EQYD 320DZ-SL003	334	2.8	315	2.75	EWYD320-BZSL	334	2.83	315	2.75
Guarda	Toshiba	MMY-MAP0802FT8	25	3.97	22.4	3.69	MMY-MAP0806FT8P-E	25	4.14	22.4	3.76
	Toshiba	MMY-MAP1002FT8-E	31.5	3.77	28	3.41	MMY-MAP1006FT8P-E	31.5	3.97	28	3.51
Coimbra	Trane	GW-1335-G0	137	2.98	120	2.45	EWYQ-G-XS120	137	3.2	127	2.84
Lisboa Building B	Climavene	SME 1202	n.a.		335	2.23	NECS-W/B 1104			328	4.3
	Climavene	HPAN/SL 1004	266	2.4	240	2.66	NECS-Q/B0904	209	2.9	198	2.49
Lisboa Building C	Daikin	EUWY N070CZ6YL	167.4	2.35	165.8	2.31	EWYQ-G-XS160	170	3.13	165	2.85
	Daikin	EWYQ 180DAYNN	199	2.87	183	2.93	EWYQ-F-XR 180	197	3.2	178	2.86
Faro	Daikin	EWYD 130DAYN	149	3	136	2.9	EWYQ-G-XS120	138	3.2	127	2.84
	Daikin	EWYD 100DAYN	114	3	100	2.9	EWYQ-G-XS085	91.5	3.12	88.1	2.8

The Table 23 shows the equipment purchase and installation costs on the basis of the various models that will replace the existing ones.

Table 23: Equipment purchase and installation cost of the new HVAC systems

Office	New Model	Quantity	Total equipment purchase (€)	Total installation costs (€)
Penafiel	Toshiba MMY-MAP0806FT8P-E	2	8,458.46	5,920.92
	Toshiba MMY-AP3016HT8P-E	1	11,954.25	8,367.98
Porto Building A	Daikin EWAD190TZ -PL B1	2	96,434.00	67,503.8
	Daikin EWYD320-BZSS	1	91,856.00	64,299.2
Porto Building B	Daikin EWAD220TZ -PL B1	2	109,270.00	76,489.00
	Daikin EWYD320-BZSL	1	96,445.00	67,511.50
Guarda	Toshiba MMY-MAP0806FT8P-E	1	4,229.23	2,960.46
	Toshiba MMY-MAP1006FT8P-E	1	4,745.13	3,321.59
Coimbra	Daikin EWYQ-G-XS120	1	32,743.00	22,920.10
Lisbon Building B	Climaveneta NECS-W/B 1104	1	35,167.15	24,617.01
	Climavaneta NECS-Q/B0904	1	38,510.00	26,957.00
Lisbon Building C	Daikin EWYQ-G-XS160	2	77,376.00	54,163.20
	Daikin EWYQ-F-XR 180	1	53,415.00	37,390.50
Faro	Daikin EWYQ-G-XS120	1	32,743.00	22,920.10
	Daikin EWYQ-G-XS085	1	25,702.00	17,991.40

After purchasing and installing the HVAC systems, operation and maintenance costs are incurred. These will be analysed and reported annually to facilitate calculations, by convention.

The operation costs in the specific case of HVAC systems can also be called energy costs. The latter were calculated based on the average annual consumption of past years extrapolated from energy certificates and updated according to the efficiency of the new plant to be installed.

In particular, the available data was the average annual consumption (E_a), distinguishing between heating and cooling for each single plant model, and the main features of the installed HVAC system (nominal power (P_{nom})

and EER for cooling or COP for heating). With these data, it is possible to derive the output power (P_{out}) and the annual utilization factor (h_a), through the formulas (3.4) (3.5):

$$P_{out} = \frac{P_{nom}}{EER\ or\ COP} \tag{3.4}$$

$$h_a = \frac{E_a}{P_{out}} < 8760 \tag{3.5}$$

Subsequently, it is assumed that the annual utilization factor remains constant for the two systems (old and new), being possible to derive, thanks to the characteristics of the new plant, the new energy consumption per year with the formula (3.6):

$$E_a^{new} = h_a \times \left(\frac{P_{nom}^{new}}{(EER\ or\ COP)^{new}}\right) \tag{3.6}$$

Finally, in order to have the total annual energy consumption for the entire building, all annual partial energy consumption has been added together. The result obtained are shown in the Table 24.

Table 24: Total annual energy consumption

Building	Total old annual energy consumption (kWh/m^{2}year)	Total new annual energy consumption (kWh/m^{2}year)	Difference (%)
Penafiel	24.66	24.25	- 1.68
Porto Building A	37.05	36.92	- 0.35
Porto Building B	88.17	82.68	- 6.23
Guarda	18.41	17.60	- 4.44
Coimbra	30.55	28.18	- 7.76
Lisbon Building B	17.04	15.71	- 7.81
Lisbon Building C	39.98	27.15	- 32.08
Faro	11.83	10.86	- 8.18

After that, based on the predictions of the World Bank (climateknowledgeportal.worldbank.org, 2019) (Figure 28), the total temperature increase in Portugal over the next 20 years will be 0.22 ° C, which translates into an increase of 1.10% on annual energy consumption, driven by the increase of the temperature in summer that offset the decrease in winter.

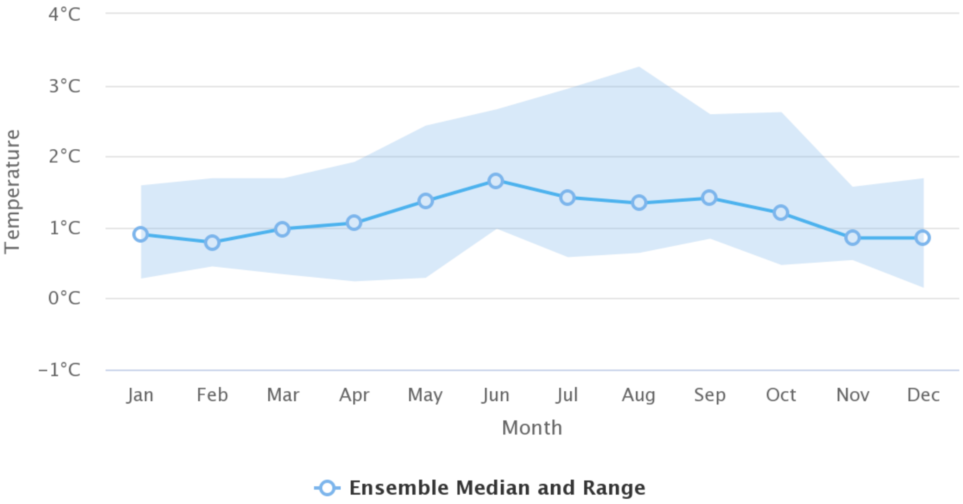
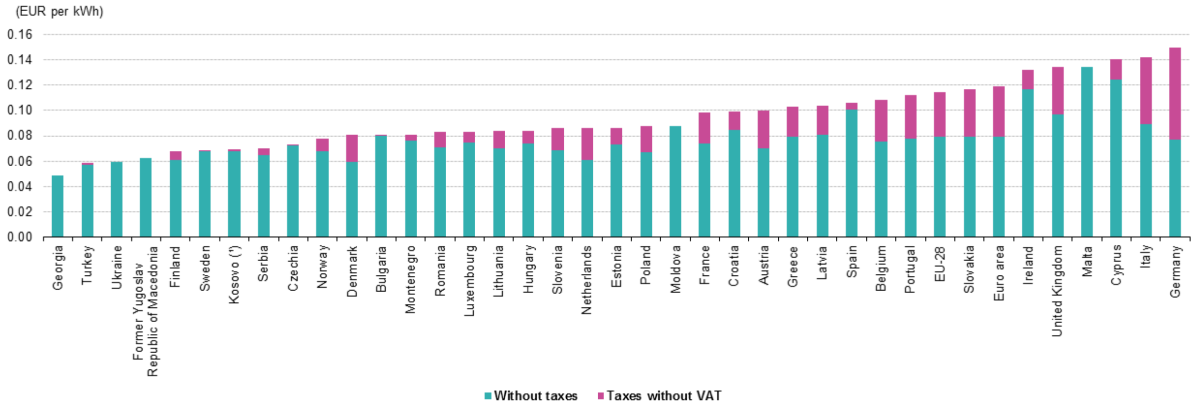


Figure 28: Projected Change in Monthly Temperature for Portugal for 2020-39

The cost of electricity is equal to 0.11 €/KW (Eurostat) (Figure 29), commercial mono-hourly tariff with taxes, with an annual Electricity Price Escalation of 1.50% based on historical data (analysis based on 2000-2018 period).



(1) This designation is without prejudice to positions on status, and is in line with UNSCR 1244/1999 and the ICJ Opinion on the Kosovo Declaration of Independence.
Source: Eurostat (online data codes: nrg_pc_205)

Figure 29: Electricity prices for non-household consumers in EU (Eurostat)

To be able to have the optimal performance of the system, it is necessary to schedule pre-established checks and maintenance interventions. In the offices studied in this thesis, it was possible to receive a list of all the ordinary maintenance carried out of the installations. Such maintenance varies according to the type of system (VRF of Chiller), and the criteria chosen is the time, for example, general cleaning, control of the oil levels of the compressor, etc., are carried out monthly. Other types of maintenance are carried out quarterly, semi-annually or yearly.

Given the lack of information, it was not possible to accurately establish the annual costs of ordinary maintenance, and therefore, consulting some technicians, it can be assumed that on average this is 5% of the equipment purchase per year for each HVAC system (ARSHAE, 2012). In addition, an increase in the costs at inflation of 2% (ecb.europa.eu, 2019) was assumed on each of the forecasted years.

Although periodic maintenance is programmed, it is possible that parts of the system undergo damage or breakage. It is extremely rare that a plant does not need any special maintenance during its life cycle, so it is advisable to include them in the LCCA. Even if it is not possible to foresee such extraordinary events, one can hypothesize for the calculation of the incurred cost, an indicative 3% of the purchase price, which can be assumed to be sustained every 5 years (ARSHAE, 2012).

The discount rate value is 1.13% (10-Y Portuguese government bond yield as of April 26, 2019) and is equivalent to the value of the 10-year Portugal bond.

Finally, at the end of the 20 years, the various HVAC systems may have a salvage value. In Table 25 presents the different forecasted salvage values of all new systems to install. The salvage value was computed by using the sum-of-the digits depreciation (Scott, 2018) with the following formula (3.7):

$$SV = \frac{K}{\sum_{i=1}^{n} Y_i} \times D \qquad (3.7)$$

Where:

SV - salvage value

K - remaining useful life of the asset

Y_i - sum of the years´ digits

D - depreciable cost

Table 25: Salvage value of the new HVAC systems

City	New Model	Quantity	Total salvage value (€)
Penafiel	Toshiba MMY-MAP0806FT8P-E	2	768.95
	Toshiba MMY-AP3016HT8P-E	1	1,086.75
Porto Building A	Daikin EWAD190TZ -PL B1	2	8,766.73
	Daikin EWYD320-BZSS	1	8,350.55
Porto Building B	Daikin EWAD220TZ -PL B1	2	9,933.64
	Daikin EWYD320-BZSL	1	8,767.73
Guarda	Toshiba MMY-MAP0806FT8P-E	1	384.48
	Toshiba MMY-MAP1006FT8P-E	1	431.38
Coimbra	Daikin EWYQ-G-XS120	1	2,976.64
Lisbon Building B	Climaveneta NECS-W/B 1104	1	3,197.01
	Climavaneta NECS-Q/B0904	1	3,500.91
Lisbon Building C	Daikin EWYQ-G-XS160	2	7,034.18
	Daikin EWYQ-F-XR 180	1	4,855.91
Faro	Daikin EWYQ-G-XS120	1	2,976.64
	Daikin EWYQ-G-XS085	1	2,336.55

3.3.3 SENSITIVITY ANALYSIS

Given that, for the calculation of the LCCA, assumptions are used, thus they have a degree of uncertainty, it is advisable to include a sensitivity analysis (SA) on specific highly variable parameters.

Sensitivity analysis is a procedure to study quantitatively and qualitatively how the variation of an uncertain parameter affects the final outcome of LCCA. In fact, with this method, it is possible to slightly manipulate some inputs to see what impact they have on the result (Marenjak & Krstić, 2010).

With regard to the HVAC system and the model adopted in this thesis it is possible to affirm that:

- CAPEX, which includes equipment and installation cost, is assumed to run all in year 0. It is a variable that is chosen at the beginning of the project and therefore is not uncertain

- For routine maintenance, a list of periodic processes has been set in such a way as to avoid damages. Its cost is relatively fixed every year and therefore is not a variable that particularly influences the result
- The cost of extraordinary maintenance is not possible to predict, so it should be an uncertain variable. However, it is not necessary to run a SA on it, as it is an indeterministic event
- The energy cost is instead an uncertain parameter because it is not possible to predict, with a reasonable degree of certainty, the energy consumption year by year. It highly depends on the climatic conditions, that differ year over year, and being a recurring cost that affects a lot on the output, it is useful to run a SA
- The discount rate is another variable with high degree of uncertainty, because it varies according to the trends of the financial markets and the economy, thus it is advised to run a SA

4 RESULTS

4.1 GENERAL CONSIDERATION

In this chapter, the results obtained by LCCA and SA will be reported and analysed.

It is also inserted an analysis on how much will be possible to save in the energy bill if it is decided to replace the equipment. This is because all the HVAC systems analysed are less than 20 years old and theoretically, have not yet reached the end of the useful life.

4.2 LIFE-CYCLE COST ANALYSIS RESULTS

In the Table 26 the results of the LCCA are presented:

Table 26: Life-cycle cost analysis results

Building	LCCA (€)	LCCA (€/m²)
Penafiel	155,515	97.79
Porto Building A	1,669,978	137.73
Porto Building B	2,615,457	207.95
Guarda	73,573	68.19
Coimbra	572,944	85.77
Lisbon Building B	612,554	58.06
Lisbon Building C	788,202	134.42
Faro	260,458	74.00

The Figure 30 analyses the impact of the main cost drivers, included in the analysis, on the final result.

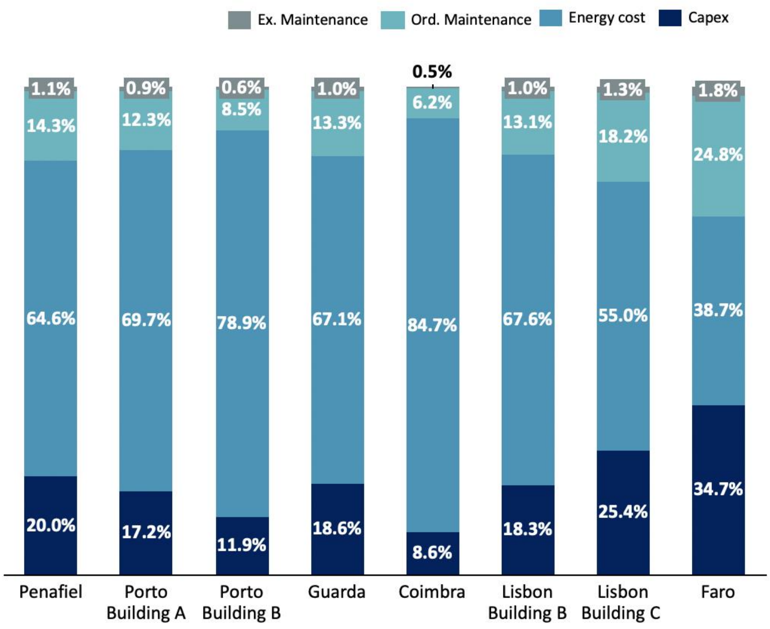


Figure 30: Impact of the main cost drivers on the Life-cycle cost analysis

4.3 SENSITIVITY ANALYSIS RESULTS

In addition, the SA was performed for the energy consumption increment and the discount rate for all buildings covered by the thesis.

In the following tables, are shown how the LCCA result varies based on simultaneous variations of-0.9%, 0.1%, 1.1%, 2.1%, and 3.1% for the energy consumption increment and 0.5%, 0.9%, 1.1%, 2.2%, and 2.7% for the discount rate.

Table 27: Penafiel's LCCA sensitivity analysis

		Energy consumption increment				
		-0.9%	0.1%	1.1%	2.1%	3.1%
Discount rate	0.5%	145,127.25	154,010.99	164,048.79	175,399.26	188,242.78
	0.9%	140,654.43	149,054.84	158,538.80	169,254.63	181,370.89
	1.1%	138,196.41	146,332.94	155,514.65	165,884.27	177,603.98
	2.2%	127,756.02	134,786.46	142,702.49	151,623.64	161,685.63
	2.7%	123,385.68	129,960.86	137,356.55	145,682.89	155,064.88

Table 28: Porto Building A's LCCA sensitivity analysis

		Energy consumption increment				
		-0.9%	0.1%	1.1%	2.1%	3.1%
Discount rate	0.5%	1,545,927.16	1,649,061.54	1,765,593.70	1,897,365.23	2,046,469.97
	0.9%	1,496,232.46	1,593,755.71	1,703,858.23	1,828,261.88	1,968,923.72
	1.1%	1,468,925.04	1,563,384.71	1,669,978.34	1,790,362.82	1,926,420.98
	2.2%	1,352,954.13	1,434,572.89	1,526,472.74	1,630,041.41	1,746,854.50
	2.7%	1,304,417.21	1,380,750.77	1,466,609.88	1,563,273.21	1,672,191.89

Table 29: Porto building B's LCCA sensitivity analysis

		Energy consumption increment				
		-0.9%	0.1%	1.1%	2.1%	3.1%
Discount rate	0.5%	2,385,088.10	2,568,935.84	2,776,666.52	3,011,562.95	3,277,357.64
	0.9%	2,302,458.05	2,476,303.37	2,672,572.55	2,894,334.97	3,145,079.31
	1.1%	2,257,058.28	2,425,442.44	2,615,456.67	2,830,054.50	3,072,592.30
	2.2%	2,064,298.84	2,209,792.76	2,373,613.78	2,558,235.70	2,766,467.16
	2.7%	1,983,647.57	2,119,720.07	2,272,772.85	2,445,085.27	2,639,244.13

Table 30: Guarda's LCCA sensitivity analysis

		Energy consumption increment				
		-0.9%	0.1%	1.1%	2.1%	3.1%
Discount rate	0.5%	68,382.42	72,756.16	77,698.07	83,286.26	89,609.51
	0.9%	66,229.61	70,365.39	75,034.63	80,310.36	86,275.57
	1.1%	65,046.59	69,052.45	73,572.89	78,678.17	84,448.14
	2.2%	60,022.10	63,483.40	67,380.70	71,772.86	76,726.68
	2.7%	57,919.03	61,156.20	64,797.33	68,896.64	73,515.68

Table 31: Coimbra’s LCCA sensitivity analysis

		Energy consumption increment				
		-0.9%	0.1%	1.1%	2.1%	3.1%
Discount rate	0.5%	517,493.89	560,851.90	609,842.38	665,239.54	727,923.64
	0.9%	498,729.68	539,728.76	586,016.20	638,315.88	697,450.55
	1.1%	488,420.74	528,131.87	572,944.17	623,554.17	680,753.44
	2.2%	444,656.90	478,969.68	517,604.66	561,145.25	610,253.83
	2.7%	426,349.03	458,439.90	494,535.33	535,172.90	580,962.65

Table 32: Lisbon Building B's LCCA sensitivity analysis

		Energy consumption increment				
		-0.9%	0.1%	1.1%	2.1%	3.1%
Discount rate	0.5%	568,917.35	605,592.99	647,033.02	693,892.33	746,915.51
	0.9%	550,937.39	585,617.66	624,771.25	669,010.46	719,031.26
	1.1%	541,057.05	574,647.88	612,553.67	655,363.62	703,747.30
	2.2%	499,094.12	528,118.59	560,799.12	597,629.20	639,169.13
	2.7%	481,530.29	508,675.29	539,207.67	573,582.14	612,314.74

Table 33: Lisbon Building C's LCCA sensitivity analysis

		Energy consumption increment				
		-0.9%	0.1%	1.1%	2.1%	3.1%
Discount rate	0.5%	746,614.34	784,798.46	827,942.92	876,729.56	931,933.59
	0.9%	725,415.74	761,522.41	802,286.39	848,345.17	900,423.32
	1.1%	713,764.34	748,736.76	788,201.62	832,772.35	883,146.05
	2.2%	664,260.19	694,478.44	728,503.12	766,848.03	810,096.50
	2.7%	643,530.24	671,791.72	703,579.90	739,368.20	779,693.87

Table 34: Faro's LCCA sensitivity analysis

		Energy consumption increment				
		-0.9%	0.1%	1.1%	2.1%	3.1%
Discount rate	0.5%	252,876.63	261,683.21	271,633.82	282,885.70	295,617.66
	0.9%	246,691.17	255,018.62	264,420.20	275,042.95	287,053.97
	1.1%	243,290.37	251,356.22	260,458.18	270,737.73	282,355.65
	2.2%	228,832.21	235,801.59	243,648.86	252,492.52	262,467.11
	2.7%	222,773.36	229,291.44	236,622.89	244,876.91	254,177.41

4.4 ENERGY COST SAVING

With the life-cycle cost analysis results it is not possible to decide which system is recommended to replace. It is however analysed the possible savings, to define the installed HVAC systems suggested to replace. For this calculation, only the operation cost is included as it is assumed that the ordinary and extraordinary maintenance will be the same for the installed and new models. The energy cost saving was calculated by comparing the energy cost of the installed systems with the estimated energy bills of the new HVAC systems, from the start year of the new plant until the end of life of the HVAC systems installed in the offices to be analysed. The total energy cost savings derives from the comparison of the annual operation cost of HVAC systems already installed with the new ones proposed in this thesis and it is related with the equipment purchase of the new system (total energy cost saving in %). Then, it is assumed that the lifetimes of the installed systems continue over 20 years, allowing to compute the payback period. Table 35 and Figure 31 shows the results of the energy cost savings analysis.

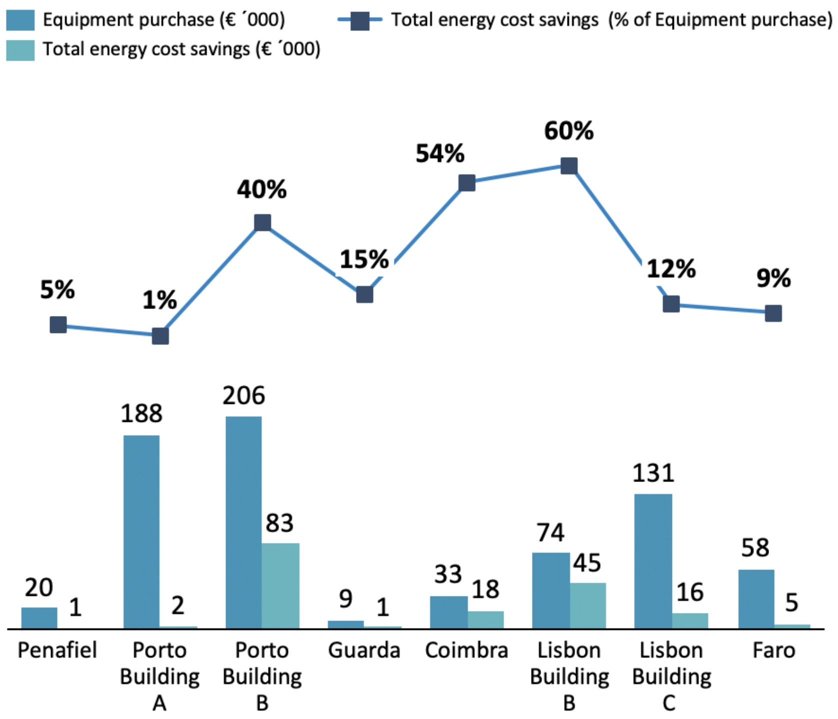


Figure 31: Energy cost saving of the new HVAC systems (graph)

Table 35: Energy cost saving of the new HVAC systems (table)

Building	Old system est. installation year	Old system Est. useful life in years	New equipment purchase (€)	Total energy cost saving (€)	Total energy cost saving (%)
Penafiel	2011	11	20,413	1,027	5
Porto Building A	2011	11	188,290	2,438	1
Porto Building B	2011	11	205,715	82,635	40
Guarda	2011	11	8,974	1,377	15
Coimbra	2008	8	32,743	17,797	54
Lisbon Building B	2004	4	73,677	44,506	60
Lisbon Building C	2008	8	130,791	15,772	12
Faro	2011	11	58,445	5,314	9

5 CONCLUSION

5.1 GENERAL CONSIDERATION

The conclusions of the analysis carried out are discussed in this final chapter, starting from a summary of the thesis, then the topics covered in the thesis. Then last topic is focused on the general conclusion of the results obtained. In this part are also inserted my suggestions for the future, with a personal fact-based opinion on the decision that the company can make for the future.

5.2 SUMMARY AND GENERAL CONCLUSION

The thesis aims to estimate economically the complete or partial replacement of heating and air-conditioning systems, maintaining the existing distribution and delivery components, in buildings used for offices, using the Life-Cycle Cost Analysis.

The thesis was divided into two macro-topics, the first of the HVAC system, describing the classifications, the components, and the main typologies. The second argument relates to the methodology for LCCA and how it is applied for the case studies addressed in this thesis.

The commissioned buildings are ten, but two of them (Leiria and Lisbon building A) were inaugurated in 2016 and therefore the plants are new, and it is not necessary to carry out the LCCA. The remaining eight buildings are located in the following cities: Penafiel, Porto (in which there two buildings), Guarda, Coimbra, Lisbon (with two buildings to be treated) and Faro.

The LCCA analyses all the possible costs that you face during the life cycle of a product/process or activity, discounted at the present time. Specifically, the costs of the HVAC system are equipment, installation, operation or energy, ordinary and extraordinary maintenance.

From the results obtained it is possible to see from the Figure 30 that the component which has the most impact on the total cost is the energy, with an average percentage of the total cost exceeding 60%. The lowest value is in Faro (35%) and the highest in Coimbra (85%). The second component in order of importance is the CAPEX, which includes the equipment purchase and the installation cost, with an average impact of 19% on the result. Next, the O&M cost, represents, on average, 13%, and finally, the smallest component is the cost of extraordinary maintenance, representing 1% of the total cost on average.

To compare effectively the results obtained with LCCA, the cost per m^2 was calculated as shown in Table 25. Is therefore possible to note that the highest cost occurs in Porto Building B (216% higher than offices' median), caused mainly by the highest annual energy consumption per square meter, as shown in Table 23. Thus, is therefore possible to assumed that there are some energy usage inefficiencies from the occupants, maybe due to the position of the building. The before mentioned reasoning is based on the comparison with the neighbourhood Porto Building A, that has the same building architectural style with 26% more surface and 49%

less cost per square meter. Even though, Lisbon Building B with the second highest surface presents the lowest estimated cost per square meter (-41% higher than offices' median), mainly due to the fact that has one of the lowest energy consumptions per square meter.

The annual energy consumption results (Table 23), are in line with the (Griffith et al., 2007), as the range of the energy variation of the paper is similar, though the countries where the buildings are located are in U.S.

(Boyano et al., 2013) reports the energy consumption of the HVAC system in the office located in Madrid. Knowing that the variation on the climate temperature in Madrid are ranging from an average minimum of 6°C in winter to an average maximum of 27°C in summer (World Meteorological Organization). This can be comparable with the climate situation in the cities of Coimbra, Porto, Penafiel, and Guarda. Looking the annual energy results obtained in the Figure 23 and the results reported in the paper, is possible to say that the conclusions are similar. On the contrary, Tallinn's climate is completely different to the Portuguese one, ranging from an average minimum of -5°C in winter to an average maximum of 18°C in summer (WMO, 2019). Thus, is understandable that the value reported in the paper is higher as it requires more energy to reach the comfort temperature for the occupants during year due to the rigid climate.

By running the sensitivity analysis with a predeterminate scenario, it is possible to note that the highest cost occurs when the discount rate is 0.5% and the energy consumption increment is 3.1%, while the lowest happens with 2.7% and -0.9% respectively. This is because, by increasing the annual energy consumption, the result of LCCA increases accordingly, while decreasing the discount rate results in a higher final cost, since hypothetically, to get the future value at n=20, is needed to invest more capital today as it will growth at lower interest rate compared to the standard scenario. Applying the same principle by decreasing the consumption of energy and increasing the discount rate, the end result will be lower.

5.3 SUGGESTIONS FOR THE FUTURE

Considering the results obtained, from the Tables 22 and 35, it is possible to advise to replace the HVAC systems in the offices of Coimbra and Lisbon Building B for the following reasons:

- Comparing the model installed with the new one, there is a significant efficiency and it can be deduced that there has been a generational leap between the two models;
- For Coimbra, the estimated total energy cost saving is €17.797 in 8 years with an average yearly saving of 7.76%. The total saved value is equal to 54% of the new equipment purchase, with a payback period of about 15 years (Table A.5). Similarly, for the office Lisbon Building B, in just 4 years, the estimated energy cost saving is €44.504, with an average yearly saving of 32.09%, which in total corresponds to 60% of the equipment purchase, with a payback period of about 8 years (Table A.6).

Regarding the Porto Building B office, it is not convenient to change all the facilities but only the two Daikin EWAD210E-SL002, being that the new model has much better efficiency. In addition, after 11 years, the total estimated energy cost saving is €74.323, which is equivalent to 68% of the equipment cost, with a payback period of 17 years (Table B.3).

For all the other buildings studied in this thesis, excluding Lisbon Building C, which has plants of 2008, all systems are relatively recent and have still more than half of the projected useful life. It can be inferred that, in the previous project, the choice of the plants adopted was an optimal solution for the technology at the time, with high energy efficiency. Moreover, in recent years the manufacturers have not produced competitive models that can justify replacement cost for these offices, thus is not convenient to replace the HAC systems present in these offices.

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ANNEX

A ANNEX – LIFE-CYCLE COST ANALISIS

Table A. 1: Penafiel’s LCCA

Item	Model	FY18	FY19	FY20	FY21	FY22	FY23	FY24	FY25	FY26	FY27	FY28	FY29	FY30	FY31	FY32	FY33	FY34	FY35	FY36	FY37	FY38
Installation Cost	MMY0MAP0806FT8P0E	€ 14,379.38	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -
	MMY0AP3016HT8P0E	€ 20,322.23	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -
	Total Installation Cost	**€ 34,701.61**	**€ -**	**€ -**	**€ -**	**€ -**	**€ -**	**€ -**	**€ -**	**€ -**	**€ -**	**€ -**	**€ -**	**€ -**	**€ -**	**€ -**	**€ -**	**€ -**	**€ -**	**€ -**	**€ -**	**€ -**
Energy	MMY0MAP0806FT8P0E	€ -	€ 884.43	€ 907.57	€ 931.32	€ 955.69	€ 980.69	€ 1,006.35	€ 1,032.68	€ 1,059.70	€ 1,087.43	€ 1,115.88	€ 1,145.08	€ 1,175.04	€ 1,205.78	€ 1,237.33	€ 1,269.71	€ 1,302.93	€ 1,337.02	€ 1,372.01	€ 1,407.90	€ 1,444.74
	MMY0AP3016HT8P0E	€ -	€ 3,446.24	€ 3,536.41	€ 3,628.94	€ 3,723.90	€ 3,821.33	€ 3,921.32	€ 4,023.92	€ 4,129.20	€ 4,237.24	€ 4,348.11	€ 4,461.88	€ 4,578.62	€ 4,698.42	€ 4,821.36	€ 4,947.51	€ 5,076.96	€ 5,209.80	€ 5,346.11	€ 5,486.00	€ 5,629.54
	Total Energy	**€ -**	**€ 4,330.67**	**€ 4,443.98**	**€ 4,560.26**	**€ 4,679.58**	**€ 4,802.02**	**€ 4,927.67**	**€ 5,056.60**	**€ 5,188.91**	**€ 5,324.67**	**€ 5,463.99**	**€ 5,606.96**	**€ 5,753.66**	**€ 5,904.21**	**€ 6,058.69**	**€ 6,217.22**	**€ 6,379.89**	**€ 6,546.82**	**€ 6,718.12**	**€ 6,893.90**	**€ 7,074.28**
O&M	MMY0MAP0806FT8P0E	€ -	€ 422.92	€ 431.38	€ 440.01	€ 448.81	€ 457.79	€ 466.94	€ 476.28	€ 485.81	€ 495.52	€ 505.43	€ 515.54	€ 525.85	€ 536.37	€ 547.10	€ 558.04	€ 569.20	€ 580.58	€ 592.19	€ 604.04	€ 616.12
	MMY0AP3016HT8P0E	€ -	€ 597.71	€ 609.67	€ 621.86	€ 634.30	€ 646.98	€ 659.92	€ 673.12	€ 686.58	€ 700.32	€ 714.32	€ 728.61	€ 743.18	€ 758.04	€ 773.20	€ 788.67	€ 804.44	€ 820.53	€ 836.94	€ 853.68	€ 870.75
	Total O&M	**€ -**	**€ 1,020.64**	**€ 1,041.05**	**€ 1,061.87**	**€ 1,083.11**	**€ 1,104.77**	**€ 1,126.86**	**€ 1,149.40**	**€ 1,172.39**	**€ 1,195.84**	**€ 1,219.75**	**€ 1,244.15**	**€ 1,269.03**	**€ 1,294.41**	**€ 1,320.30**	**€ 1,346.71**	**€ 1,373.64**	**€ 1,401.11**	**€ 1,429.14**	**€ 1,457.72**	**€ 1,486.87**
Ex. Mainteinence	MMY0MAP0806FT8P0E	€ -	€ -	€ -	€ -	€ -	€ 253.75	€ -	€ -	€ -	€ -	€ 253.75	€ -	€ -	€ -	€ -	€ 253.75	€ -	€ -	€ -	€ -	€ -
	MMY0AP3016HT8P0E	€ -	€ -	€ -	€ -	€ -	€ 358.63	€ -	€ -	€ -	€ -	€ 358.63	€ -	€ -	€ -	€ -	€ 358.63	€ -	€ -	€ -	€ -	€ -
	Total Ex. Mainteinence	**€ -**	**€ -**	**€ -**	**€ -**	**€ -**	**€ 612.38**	**€ -**	**€ -**	**€ -**	**€ -**	**€ 612.38**	**€ -**	**€ -**	**€ -**	**€ -**	**€ 612.38**	**€ -**	**€ -**	**€ -**	**€ -**	**€ -**
Savage Value	MMY0MAP0806FT8P0E	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ 768.95
	MMY0AP3016HT8P0E	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ 1,086.75
	Total Savage Value	**€ -**	**€ -**	**€ -**	**€ -**	**€ -**	**€ -**	**€ -**	**€ -**	**€ -**	**€ -**	**€ -**	**€ -**	**€ -**	**€ -**	**€ -**	**€ -**	**€ -**	**€ -**	**€ -**	**€ -**	**€ 1,855.70**
Total Cost	**Grand Total**	**€ 34,701.61**	**€ 5,351.31**	**€ 5,485.03**	**€ 5,622.13**	**€ 5,762.69**	**€ 6,519.17**	**€ 6,054.53**	**€ 6,206.00**	**€ 6,361.29**	**€ 6,520.51**	**€ 7,296.13**	**€ 6,851.11**	**€ 7,022.70**	**€ 7,198.62**	**€ 7,378.99**	**€ 8,176.31**	**€ 7,753.53**	**€ 7,947.94**	**€ 8,147.26**	**€ 8,351.62**	**€ 6,705.45**
PV	**PV Total Cost**	**€ 34,701.61**	**€ 5,291.51**	**€ 5,363.14**	**€ 5,435.77**	**€ 5,509.41**	**€ 6,163.00**	**€ 5,659.79**	**€ 5,736.56**	**€ 5,814.41**	**€ 5,893.34**	**€ 6,520.67**	**€ 6,054.53**	**€ 6,136.83**	**€ 6,220.27**	**€ 6,304.88**	**€ 6,908.08**	**€ 6,477.68**	**€ 6,565.90**	**€ 6,655.35**	**€ 6,746.06**	**€ 5,355.84**

Table A. 2: Porto Building A's LCCA

Item	Model	FY18	FY19	FY20	FY21	FY22	FY23	FY24	FY25	FY26	FY27	FY28	FY29	FY30	FY31	FY32	FY33	FY34	FY35	FY36	FY37	FY38
Installation Cost	EWAD190TZ -PL B1	€ 163,937.80	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -
	EWYD320-BZSS	€ 156,155.20	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -
	Total Installation Cost	**€ 320,093.00**	**€ -**	**€ -**	**€ -**	**€ -**	**€ -**	**€ -**	**€ -**	**€ -**	**€ -**	**€ -**	**€ -**	**€ -**	**€ -**	**€ -**	**€ -**	**€ -**	**€ -**	**€ -**	**€ -**	**€ -**
Energy	EWAD190TZ -PL B1 + EWYD320-BZSS	€ -	€ 50,276.26	€ 51,591.73	€ 52,941.63	€ 54,326.85	€ 55,748.31	€ 57,206.97	€ 58,703.79	€ 60,239.77	€ 61,815.95	€ 63,433.36	€ 65,093.09	€ 66,796.25	€ 68,543.98	€ 70,337.43	€ 72,177.81	€ 74,066.34	€ 76,004.29	€ 77,992.94	€ 80,033.63	€ 82,127.71
	Total Energy	**€ -**	**€ 50,276.26**	**€ 51,591.73**	**€ 52,941.63**	**€ 54,326.85**	**€ 55,748.31**	**€ 57,206.97**	**€ 58,703.79**	**€ 60,239.77**	**€ 61,815.95**	**€ 63,433.36**	**€ 65,093.09**	**€ 66,796.25**	**€ 68,543.98**	**€ 70,337.43**	**€ 72,177.81**	**€ 74,066.34**	**€ 76,004.29**	**€ 77,992.94**	**€ 80,033.63**	**€ 82,127.71**
O&M	EWAD190TZ -PL B1	€ -	€ 4,821.70	€ 4,918.13	€ 5,016.50	€ 5,116.83	€ 5,219.16	€ 5,323.55	€ 5,430.02	€ 5,538.62	€ 5,649.39	€ 5,762.38	€ 5,877.63	€ 5,995.18	€ 6,115.08	€ 6,237.38	€ 6,362.13	€ 6,489.37	€ 6,619.16	€ 6,751.54	€ 6,886.57	€ 7,024.31
	EWYD320-BZSS	€ -	€ 4,592.80	€ 4,684.66	€ 4,778.35	€ 4,873.92	€ 4,971.39	€ 5,070.82	€ 5,172.24	€ 5,275.68	€ 5,381.20	€ 5,488.82	€ 5,598.60	€ 5,710.57	€ 5,824.78	€ 5,941.28	€ 6,060.10	€ 6,181.30	€ 6,304.93	€ 6,431.03	€ 6,559.65	€ 6,690.84
	Total O&M	€ -	**€ 9,414.50**	**€ 9,602.79**	**€ 9,794.85**	**€ 9,990.74**	**€ 10,190.56**	**€ 10,394.37**	**€ 10,602.26**	**€ 10,814.30**	**€ 11,030.59**	**€ 11,251.20**	**€ 11,476.22**	**€ 11,705.75**	**€ 11,939.86**	**€ 12,178.66**	**€ 12,422.23**	**€ 12,670.68**	**€ 12,924.09**	**€ 13,182.57**	**€ 13,446.22**	**€ 13,715.15**
Ex. Mainteinence	EWAD190TZ -PL B1	€ -	€ -	€ -	€ -	€ -	€ 2,893.02	€ -	€ -	€ -	€ -	€ 2,893.02	€ -	€ -	€ -	€ -	€ 2,893.02	€ -	€ -	€ -	€ -	€ -
	EWYD320-BZSS	€ -	€ -	€ -	€ -	€ -	€ 2,755.68	€ -	€ -	€ -	€ -	€ 2,755.68	€ -	€ -	€ -	€ -	€ 2,755.68	€ -	€ -	€ -	€ -	€ -
	Total Ex. Mainteinence	**€ -**	**€ -**	**€ -**	**€ -**	**€ -**	**€ 5,648.70**	**€ -**	**€ -**	**€ -**	**€ -**	**€ 5,648.70**	**€ -**	**€ -**	**€ -**	**€ -**	**€ 5,648.70**	**€ -**	**€ -**	**€ -**	**€ -**	**€ -**
Savage Value	EWAD190TZ -PL B1	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ 8,766.73
	EWYD320-BZSS	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ 8,350.55
	Total Savage Value	**€ -**	**€ -**	**€ -**	**€ -**	**€ -**	**€ -**	**€ -**	**€ -**	**€ -**	**€ -**	**€ -**	**€ -**	**€ -**	**€ -**	**€ -**	**€ -**	**€ -**	**€ -**	**€ -**	**€ -**	**€ 17,117.27**
Total Cost	**Grand Total**	**€ 320,093.00**	**€ 59,690.76**	**€ 61,194.52**	**€ 62,736.48**	**€ 64,317.59**	**€ 71,587.57**	**€ 67,601.34**	**€ 69,306.04**	**€ 71,054.07**	**€ 72,846.53**	**€ 80,333.26**	**€ 76,569.32**	**€ 78,502.00**	**€ 80,483.84**	**€ 82,516.09**	**€ 90,248.74**	**€ 86,737.02**	**€ 88,928.38**	**€ 91,175.51**	**€ 93,479.85**	**€ 78,725.58**
PV	**PV Total Cost**	**€ 320,093.00**	**€ 59,023.79**	**€ 59,834.62**	**€ 60,656.89**	**€ 61,490.74**	**€ 67,676.45**	**€ 63,193.91**	**€ 64,063.56**	**€ 64,945.48**	**€ 65,839.85**	**€ 71,795.18**	**€ 67,666.65**	**€ 68,599.45**	**€ 69,545.43**	**€ 70,504.78**	**€ 76,250.21**	**€ 72,464.35**	**€ 73,464.96**	**€ 74,479.73**	**€ 75,508.85**	**€ 62,880.46**

Table A. 3 : Porto Building B's LCCA

Item	Model	FY18	FY19	FY20	FY21	FY22	FY23	FY24	FY25	FY26	FY27	FY28	FY29	FY30	FY31	FY32	FY33	FY34	FY35	FY36	FY37	FY38
Installation Cost	EWAD220TZ -PL B1	€ 185,759.00	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -
	EWYD320-BZSL	€ 163,956.50	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -
	Total Installation Cost	**€ 349,715.50**	**€ -**	**€ -**	**€ -**	**€ -**	**€ -**	**€ -**	**€ -**	**€ -**	**€ -**	**€ -**	**€ -**	**€ -**	**€ -**	**€ -**	**€ -**	**€ -**	**€ -**	**€ -**	**€ -**	**€ -**
Energy	EWAD220TZ -PL B1	€ -	€ 26,941.78	€ 27,646.71	€ 28,370.09	€ 29,112.39	€ 29,874.11	€ 30,655.77	€ 31,457.88	€ 32,280.97	€ 33,125.61	€ 33,992.34	€ 34,881.75	€ 35,794.43	€ 36,730.99	€ 37,692.06	€ 38,678.27	€ 39,690.29	€ 40,728.78	€ 41,794.45	€ 42,888.00	€ 44,010.17
	EWYD320-BZSL	€ -	€ 62,680.87	€ 64,320.91	€ 66,003.87	€ 67,730.86	€ 69,503.04	€ 71,321.59	€ 73,187.72	€ 75,102.67	€ 77,067.73	€ 79,084.21	€ 81,153.45	€ 83,276.83	€ 85,455.77	€ 87,691.72	€ 89,986.17	€ 92,340.66	€ 94,756.75	€ 97,236.06	€ 99,780.25	€ 102,391.00
	Total Energy	**€ -**	**€ 89,622.65**	**€ 91,967.62**	**€ 94,373.96**	**€ 96,843.25**	**€ 99,377.15**	**€ 101,977.36**	**€ 104,645.60**	**€ 107,383.65**	**€ 110,193.34**	**€ 113,076.55**	**€ 116,035.20**	**€ 119,071.26**	**€ 122,186.76**	**€ 125,383.77**	**€ 128,664.44**	**€ 132,030.95**	**€ 135,485.54**	**€ 139,030.51**	**€ 142,668.25**	**€ 146,401.16**
O&M	EWAD220TZ -PL B1	€ -	€ 5,463.50	€ 5,572.77	€ 5,684.23	€ 5,797.91	€ 5,913.87	€ 6,032.15	€ 6,152.79	€ 6,275.84	€ 6,401.36	€ 6,529.39	€ 6,659.98	€ 6,793.18	€ 6,929.04	€ 7,067.62	€ 7,208.97	€ 7,353.15	€ 7,500.21	€ 7,650.22	€ 7,803.22	€ 7,959.29
	EWYD320-BZSL	€ -	€ 4,822.25	€ 4,918.70	€ 5,017.07	€ 5,117.41	€ 5,219.76	€ 5,324.15	€ 5,430.64	€ 5,539.25	€ 5,650.03	€ 5,763.04	€ 5,878.30	€ 5,995.86	€ 6,115.78	€ 6,238.09	€ 6,362.86	€ 6,490.11	€ 6,619.92	€ 6,752.31	€ 6,887.36	€ 7,025.11
	Total O&M	**€ -**	**€ 10,285.75**	**€ 10,491.47**	**€ 10,701.29**	**€ 10,915.32**	**€ 11,133.63**	**€ 11,356.30**	**€ 11,583.43**	**€ 11,815.09**	**€ 12,051.40**	**€ 12,292.42**	**€ 12,538.27**	**€ 12,789.04**	**€ 13,044.82**	**€ 13,305.71**	**€ 13,571.83**	**€ 13,843.27**	**€ 14,120.13**	**€ 14,402.53**	**€ 14,690.58**	**€ 14,984.40**
Ex. Mainteinence	EWAD220TZ -PL B1	€ -	€ -	€ -	€ -	€ -	€ 3,278.10	€ -	€ -	€ -	€ -	€ 3,278.10	€ -	€ -	€ -	€ -	€ 3,278.10	€ -	€ -	€ -	€ -	€ -
	EWYD320-BZSL	€ -	€ -	€ -	€ -	€ -	€ 2,893.35	€ -	€ -	€ -	€ -	€ 2,893.35	€ -	€ -	€ -	€ -	€ 2,893.35	€ -	€ -	€ -	€ -	€ -
	Total Ex. Mainteinence	**€ -**	**€ -**	**€ -**	**€ -**	**€ -**	**€ 6,171.45**	**€ -**	**€ -**	**€ -**	**€ -**	**€ 6,171.45**	**€ -**	**€ -**	**€ -**	**€ -**	**€ 6,171.45**	**€ -**	**€ -**	**€ -**	**€ -**	**€ -**
Savage Value	EWAD220TZ -PL B1	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ 9,933.64
	EWYD320-BZSL	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ 8,767.73
	Total Savage Value	**€ -**	**€ -**	**€ -**	**€ -**	**€ -**	**€ -**	**€ -**	**€ -**	**€ -**	**€ -**	**€ -**	**€ -**	**€ -**	**€ -**	**€ -**	**€ -**	**€ -**	**€ -**	**€ -**	**€ -**	**€ 18,701.36**
Total Cost	**Grand Total**	**€ 349,715.50**	**€ 99,908.40**	**€ 102,459.09**	**€ 105,075.25**	**€ 107,758.57**	**€ 116,682.23**	**€ 113,333.66**	**€ 116,229.02**	**€ 119,198.74**	**€ 122,244.74**	**€ 131,540.42**	**€ 128,573.47**	**€ 131,860.30**	**€ 135,231.58**	**€ 138,689.49**	**€ 148,407.72**	**€ 145,874.21**	**€ 149,605.67**	**€ 153,433.05**	**€ 157,358.83**	**€ 142,684.19**
PV	**PV Total Cost**	**€ 349,715.50**	**€ 98,792.05**	**€ 100,182.18**	**€ 101,592.21**	**€ 103,022.43**	**€ 110,307.41**	**€ 105,944.61**	**€ 107,437.16**	**€ 108,951.10**	**€ 110,486.73**	**€ 117,559.89**	**€ 113,624.32**	**€ 115,226.92**	**€ 116,852.50**	**€ 118,501.39**	**€ 125,388.12**	**€ 121,870.45**	**€ 123,591.31**	**€ 125,336.85**	**€ 127,107.44**	**€ 113,966.11**

Table A. 4: Guarda's LCCA

Item	Model	FY18	FY19	FY20	FY21	FY22	FY23	FY24	FY25	FY26	FY27	FY28	FY29	FY30	FY31	FY32	FY33	FY34	FY35	FY36	FY37	FY38
Installation Cost	MMY-MAP0806FT8P-E	€ 7,189.69	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -
	MMY-MAP1006FT8P-E	€ 8,066.72	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -
	Total Installation Cost	€ 15,256.41	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -
Energy	MMY-MAP0806FT8P-E	€ -	€ 715.36	€ 734.08	€ 753.29	€ 773.00	€ 793.22	€ 813.98	€ 835.27	€ 857.13	€ 879.56	€ 902.57	€ 926.19	€ 950.42	€ 975.29	€ 1,000.80	€ 1,026.99	€ 1,053.86	€ 1,081.44	€ 1,109.73	€ 1,138.77	€ 1,168.56
	MMY-MAP1006FT8P-E	€ -	€ 1,416.76	€ 1,453.83	€ 1,491.87	€ 1,530.90	€ 1,570.96	€ 1,612.07	€ 1,654.24	€ 1,697.53	€ 1,741.94	€ 1,787.52	€ 1,834.29	€ 1,882.29	€ 1,931.54	€ 1,982.08	€ 2,033.94	€ 2,087.15	€ 2,141.76	€ 2,197.80	€ 2,255.31	€ 2,314.32
	Total Energy	€ -	€ 2,132.12	€ 2,187.91	€ 2,245.16	€ 2,303.90	€ 2,364.18	€ 2,426.04	€ 2,489.52	€ 2,554.66	€ 2,621.50	€ 2,690.09	€ 2,760.48	€ 2,832.71	€ 2,906.82	€ 2,982.88	€ 3,060.93	€ 3,141.02	€ 3,223.20	€ 3,307.54	€ 3,394.08	€ 3,482.88
O&M	MMY-MAP0806FT8P-E	€ -	€ 211.46	€ 215.69	€ 220.00	€ 224.40	€ 228.89	€ 233.47	€ 238.14	€ 242.90	€ 247.76	€ 252.72	€ 257.77	€ 262.93	€ 268.18	€ 273.55	€ 279.02	€ 284.60	€ 290.29	€ 296.10	€ 302.02	€ 308.06
	MMY-MAP1006FT8P-E	€ -	€ 237.26	€ 242.00	€ 246.84	€ 251.78	€ 256.81	€ 261.95	€ 267.19	€ 272.53	€ 277.98	€ 283.54	€ 289.21	€ 295.00	€ 300.90	€ 306.92	€ 313.05	€ 319.32	€ 325.70	€ 332.22	€ 338.86	€ 345.64
	Total O&M	€ -	€ 448.72	€ 457.69	€ 466.85	€ 476.18	€ 485.71	€ 495.42	€ 505.33	€ 515.44	€ 525.74	€ 536.26	€ 546.98	€ 557.92	€ 569.08	€ 580.46	€ 592.07	€ 603.92	€ 615.99	€ 628.31	€ 640.88	€ 653.70
Ex. Mainteinence	MMY-MAP0806FT8P-E	€ -	€ -	€ -	€ -	€ -	€ 126.88	€ -	€ -	€ -	€ -	€ 126.88	€ -	€ -	€ -	€ -	€ 126.88	€ -	€ -	€ -	€ -	€ -
	MMY-MAP1006FT8P-E	€ -	€ -	€ -	€ -	€ -	€ 142.35	€ -	€ -	€ -	€ -	€ 142.35	€ -	€ -	€ -	€ -	€ 142.35	€ -	€ -	€ -	€ -	€ -
	Total Ex. Mainteinence	€ -	€ -	€ -	€ -	€ -	€ 269.23	€ -	€ -	€ -	€ -	€ 269.23	€ -	€ -	€ -	€ -	€ 269.23	€ -	€ -	€ -	€ -	€ -
Savage Value	MMY-MAP0806FT8P-E	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ 384.48
	MMY-MAP1006FT8P-E	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ 431.38
	Total Savage Value	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ 815.85
Total Cost	Grand Total	€ 15,256.41	€ 2,580.84	€ 2,645.60	€ 2,712.00	€ 2,780.08	€ 3,119.12	€ 2,921.46	€ 2,994.85	€ 3,070.09	€ 3,147.24	€ 3,495.58	€ 3,307.46	€ 3,390.63	€ 3,475.91	€ 3,563.35	€ 3,922.23	€ 3,744.93	€ 3,839.20	€ 3,935.85	€ 4,034.96	€ 3,320.73
PV	PV Total Cost	€ 15,256.41	€ 2,552.00	€ 2,586.81	€ 2,622.11	€ 2,657.90	€ 2,948.71	€ 2,730.99	€ 2,768.31	€ 2,806.15	€ 2,844.53	€ 3,124.06	€ 2,922.91	€ 2,962.92	€ 3,003.50	€ 3,044.65	€ 3,313.85	€ 3,128.70	€ 3,171.61	€ 3,215.13	€ 3,259.26	€ 2,652.37

Table A. 5: Coimbra's LCCA

Item	Model	FY18	FY19	FY20	FY21	FY22	FY23	FY24	FY25	FY26	FY27	FY28	FY29	FY30	FY31	FY32	FY33	FY34	FY35	FY36	FY37	FY38
Installation Cost	EWYQ0G0XS120	€ 55,663.10	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -
	Total Installation Cost	€ 55,663.10	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -
Energy	EWYQ0G0XS120	€ -	€ 21,136.29	€ 21,689.32	€ 22,256.83	€ 22,839.18	€ 23,436.76	€ 24,049.99	€ 24,679.25	€ 25,324.99	€ 25,987.61	€ 26,667.58	€ 27,365.34	€ 28,081.35	€ 28,816.10	€ 29,570.07	€ 30,343.77	€ 31,137.72	€ 31,952.44	€ 32,788.47	€ 33,646.38	€ 34,526.74
	Total Energy	€ -	€ 21,136.29	€ 21,689.32	€ 22,256.83	€ 22,839.18	€ 23,436.76	€ 24,049.99	€ 24,679.25	€ 25,324.99	€ 25,987.61	€ 26,667.58	€ 27,365.34	€ 28,081.35	€ 28,816.10	€ 29,570.07	€ 30,343.77	€ 31,137.72	€ 31,952.44	€ 32,788.47	€ 33,646.38	€ 34,526.74
O&M	EWYQ0G0XS120	€ -	€ 1,637.15	€ 1,669.89	€ 1,703.29	€ 1,737.36	€ 1,772.10	€ 1,807.55	€ 1,843.70	€ 1,880.57	€ 1,918.18	€ 1,956.55	€ 1,995.68	€ 2,035.59	€ 2,076.30	€ 2,117.83	€ 2,160.18	€ 2,203.39	€ 2,247.46	€ 2,292.41	€ 2,338.25	€ 2,385.02
	Total O&M	€ -	€ 1,637.15	€ 1,669.89	€ 1,703.29	€ 1,737.36	€ 1,772.10	€ 1,807.55	€ 1,843.70	€ 1,880.57	€ 1,918.18	€ 1,956.55	€ 1,995.68	€ 2,035.59	€ 2,076.30	€ 2,117.83	€ 2,160.18	€ 2,203.39	€ 2,247.46	€ 2,292.41	€ 2,338.25	€ 2,385.02
Ex. Mainteinence	EWYQ0G0XS120	€ -	€ -	€ -	€ -	€ -	€ 982.29	€ -	€ -	€ -	€ -	€ 982.29	€ -	€ -	€ -	€ -	€ 982.29	€ -	€ -	€ -	€ -	€ -
	Total Ex. Mainteinence	€ -	€ -	€ -	€ -	€ -	€ 982.29	€ -	€ -	€ -	€ -	€ 982.29	€ -	€ -	€ -	€ -	€ 982.29	€ -	€ -	€ -	€ -	€ -
Salvage Value	EWYQ0G0XS120	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ 2,976.64
	Total Savage Value	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ 2,976.64
Total Cost	Grand Total	€ 55,663.10	€ 22,773.44	€ 23,359.22	€ 23,960.12	€ 24,576.53	€ 26,191.16	€ 25,857.53	€ 26,522.95	€ 27,205.56	€ 27,905.80	€ 29,606.42	€ 29,361.01	€ 30,116.94	€ 30,892.40	€ 31,687.90	€ 33,486.25	€ 33,341.11	€ 34,199.89	€ 35,080.88	€ 35,984.64	€ 33,935.12
PV	PV Total Cost	€ 55,663.10	€ 22,518.98	€ 22,840.11	€ 23,165.89	€ 23,496.36	€ 24,760.23	€ 24,171.69	€ 24,516.69	€ 24,866.67	€ 25,221.70	€ 26,459.75	€ 25,947.23	€ 26,317.87	€ 26,693.87	€ 27,075.31	€ 28,292.18	€ 27,854.79	€ 28,253.00	€ 28,656.97	€ 29,066.78	€ 27,104.99

Table A. 6: Lisbon Building B's LCCA

Item	Model	FY18	FY19	FY20	FY21	FY22	FY23	FY24	FY25	FY26	FY27	FY28	FY29	FY30	FY31	FY32	FY33	FY34	FY35	FY36	FY37	FY38
Installation Cost	NECS-W/B 1104	€ 59,784.16	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -
	NECS-Q/B0904	€ 65,467.00	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -
	Total Installation Cost	**€ 125,251.16**	**€ -**	**€ -**	**€ -**	**€ -**	**€ -**	**€ -**	**€ -**	**€ -**	**€ -**	**€ -**	**€ -**	**€ -**	**€ -**	**€ -**	**€ -**	**€ -**	**€ -**	**€ -**	**€ -**	**€ -**
Energy	NECS-W/B 1104	€ -	€ 6,857.79	€ 7,037.23	€ 7,221.36	€ 7,410.30	€ 7,604.20	€ 7,803.16	€ 8,007.33	€ 8,216.84	€ 8,431.83	€ 8,652.45	€ 8,878.84	€ 9,111.16	€ 9,349.55	€ 9,594.18	€ 9,845.22	€ 10,102.82	€ 10,367.16	€ 10,638.41	€ 10,916.77	€ 11,202.40
	NECS-Q/B0904	€ -	€ 11,020.96	€ 11,309.32	€ 11,605.23	€ 11,908.88	€ 12,220.48	€ 12,540.23	€ 12,868.34	€ 13,205.04	€ 13,550.55	€ 13,905.10	€ 14,268.93	€ 14,642.27	€ 15,025.39	€ 15,418.53	€ 15,821.95	€ 16,235.94	€ 16,660.75	€ 17,096.68	€ 17,544.01	€ 18,003.05
	Total Energy	**€ -**	**€ 17,878.75**	**€ 18,346.55**	**€ 18,826.59**	**€ 19,319.19**	**€ 19,824.67**	**€ 20,343.38**	**€ 20,875.67**	**€ 21,421.88**	**€ 21,982.38**	**€ 22,557.55**	**€ 23,147.77**	**€ 23,753.43**	**€ 24,374.94**	**€ 25,012.71**	**€ 25,667.17**	**€ 26,338.75**	**€ 27,027.90**	**€ 27,735.09**	**€ 28,460.78**	**€ 29,205.45**
O&M	NECS-W/B 1104	€ -	€ 1,758.36	€ 1,793.52	€ 1,829.40	€ 1,865.98	€ 1,903.30	€ 1,941.37	€ 1,980.20	€ 2,019.80	€ 2,060.20	€ 2,101.40	€ 2,143.43	€ 2,186.30	€ 2,230.02	€ 2,274.62	€ 2,320.12	€ 2,366.52	€ 2,413.85	€ 2,462.13	€ 2,511.37	€ 2,561.59
	NECS-Q/B0904	€ -	€ 1,925.50	€ 1,964.01	€ 2,003.29	€ 2,043.36	€ 2,084.22	€ 2,125.91	€ 2,168.43	€ 2,211.79	€ 2,256.03	€ 2,301.15	€ 2,347.17	€ 2,394.12	€ 2,442.00	€ 2,490.84	€ 2,540.66	€ 2,591.47	€ 2,643.30	€ 2,696.16	€ 2,750.09	€ 2,805.09
	Total O&M	**€ -**	**€ 3,683.86**	**€ 3,757.53**	**€ 3,832.69**	**€ 3,909.34**	**€ 3,987.53**	**€ 4,067.28**	**€ 4,148.62**	**€ 4,231.59**	**€ 4,316.23**	**€ 4,402.55**	**€ 4,490.60**	**€ 4,580.41**	**€ 4,672.02**	**€ 4,765.46**	**€ 4,860.77**	**€ 4,957.99**	**€ 5,057.15**	**€ 5,158.29**	**€ 5,261.46**	**€ 5,366.68**
Ex. Mainteinence	NECS-W/B 1104	€ -	€ -	€ -	€ -	€ -	€ 1,055.01	€ -	€ -	€ -	€ -	€ 1,055.01	€ -	€ -	€ -	€ -	€ 1,055.01	€ -	€ -	€ -	€ -	€ -
	NECS-Q/B0904	€ -	€ -	€ -	€ -	€ -	€ 1,155.30	€ -	€ -	€ -	€ -	€ 1,155.30	€ -	€ -	€ -	€ -	€ 1,155.30	€ -	€ -	€ -	€ -	€ -
	Total Ex. Mainteinence	**€ -**	**€ -**	**€ -**	**€ -**	**€ -**	**€ 2,210.31**	**€ -**	**€ -**	**€ -**	**€ -**	**€ 2,210.31**	**€ -**	**€ -**	**€ -**	**€ -**	**€ 2,210.31**	**€ -**	**€ -**	**€ -**	**€ -**	**€ -**
Savage Value	NECS-W/B 1104	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ 3,197.01
	NECS-Q/B0904	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ 3,500.91
	Total Savage Value	**€ -**	**€ -**	**€ -**	**€ -**	**€ -**	**€ -**	**€ -**	**€ -**	**€ -**	**€ -**	**€ -**	**€ -**	**€ -**	**€ -**	**€ -**	**€ -**	**€ -**	**€ -**	**€ -**	**€ -**	**€ 6,697.92**
Total Cost	**Grand Total**	**€ 125,251.16**	**€ 21,562.61**	**€ 22,104.08**	**€ 22,659.27**	**€ 23,228.52**	**€ 26,022.51**	**€ 24,410.66**	**€ 25,024.29**	**€ 25,653.48**	**€ 26,298.61**	**€ 29,170.42**	**€ 27,638.37**	**€ 28,333.85**	**€ 29,046.96**	**€ 29,778.17**	**€ 32,738.26**	**€ 31,296.74**	**€ 32,085.05**	**€ 32,893.38**	**€ 33,722.23**	**€ 27,874.22**
PV Cost	**Total PV Cost**	**€ 125,251.16**	**€ 21,321.68**	**€ 21,612.87**	**€ 21,908.16**	**€ 22,207.60**	**€ 24,600.80**	**€ 22,819.15**	**€ 23,131.39**	**€ 23,448.02**	**€ 23,769.10**	**€ 26,070.09**	**€ 24,424.88**	**€ 24,759.70**	**€ 25,099.24**	**€ 25,443.57**	**€ 27,660.21**	**€ 26,146.83**	**€ 26,505.90**	**€ 26,870.04**	**€ 27,239.32**	**€ 22,263.97**

Table A. 7: Lisbon Building C's LCCA

Item	Model	FY18	FY19	FY20	FY21	FY22	FY23	FY24	FY25	FY26	FY27	FY28	FY29	FY30	FY31	FY32	FY33	FY34	FY35	FY36	FY37	FY38
Installation Cost	EWYQ-G-XS160	€ 131,539.20	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -
	EWYQ-F-XR 180	€ 90,805.50	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -
	Total Installation Cost	**€ 222,344.70**	**€ -**	**€ -**	**€ -**	**€ -**	**€ -**	**€ -**	**€ -**	**€ -**	**€ -**	**€ -**	**€ -**	**€ -**	**€ -**	**€ -**	**€ -**	**€ -**	**€ -**	**€ -**	**€ -**	**€ -**
Energy	EWYQ-G-XS160	€ -	€ 5,165.88	€ 5,301.05	€ 5,439.75	€ 5,582.08	€ 5,728.14	€ 5,878.01	€ 6,031.81	€ 6,189.63	€ 6,351.59	€ 6,517.77	€ 6,688.31	€ 6,863.31	€ 7,042.89	€ 7,227.17	€ 7,416.27	€ 7,610.31	€ 7,809.44	€ 8,013.77	€ 8,223.45	€ 8,438.62
	EWYQ-F-XR 180	€ -	€ 13,448.22	€ 13,800.10	€ 14,161.18	€ 14,531.70	€ 14,911.93	€ 15,302.10	€ 15,702.48	€ 16,113.33	€ 16,534.94	€ 16,967.57	€ 17,411.53	€ 17,867.10	€ 18,334.60	€ 18,814.32	€ 19,306.60	€ 19,811.75	€ 20,330.13	€ 20,862.07	€ 21,407.92	€ 21,968.06
	Total Energy	**€ -**	**€ 18,614.11**	**€ 19,101.15**	**€ 19,600.93**	**€ 20,113.79**	**€ 20,640.06**	**€ 21,180.11**	**€ 21,734.29**	**€ 22,302.97**	**€ 22,886.52**	**€ 23,485.35**	**€ 24,099.84**	**€ 24,730.41**	**€ 25,377.49**	**€ 26,041.49**	**€ 26,722.86**	**€ 27,422.07**	**€ 28,139.57**	**€ 28,875.84**	**€ 29,631.37**	**€ 30,406.68**
O&M	EWYQ-G-XS160	€ -	€ 3,868.80	€ 3,946.18	€ 4,025.10	€ 4,105.60	€ 4,187.71	€ 4,271.47	€ 4,356.90	€ 4,444.04	€ 4,532.92	€ 4,623.57	€ 4,716.05	€ 4,810.37	€ 4,906.57	€ 5,004.71	€ 5,104.80	€ 5,206.90	€ 5,311.03	€ 5,417.25	€ 5,525.60	€ 5,636.11
	EWYQ-F-XR 180	€ -	€ 2,670.75	€ 2,724.17	€ 2,778.65	€ 2,834.22	€ 2,890.91	€ 2,948.72	€ 3,007.70	€ 3,067.85	€ 3,129.21	€ 3,191.79	€ 3,255.63	€ 3,320.74	€ 3,387.16	€ 3,454.90	€ 3,524.00	€ 3,594.48	€ 3,666.37	€ 3,739.69	€ 3,814.49	€ 3,890.78
	Total O&M	**€ -**	**€ 6,539.55**	**€ 6,670.34**	**€ 6,803.75**	**€ 6,939.82**	**€ 7,078.62**	**€ 7,220.19**	**€ 7,364.60**	**€ 7,511.89**	**€ 7,662.13**	**€ 7,815.37**	**€ 7,971.67**	**€ 8,131.11**	**€ 8,293.73**	**€ 8,459.61**	**€ 8,628.80**	**€ 8,801.37**	**€ 8,977.40**	**€ 9,156.95**	**€ 9,340.09**	**€ 9,526.89**
Ex. Mainteinence	EWYQ-G-XS160	€ -	€ -	€ -	€ -	€ -	€ 2,321.28	€ -	€ -	€ -	€ -	€ 2,321.28	€ -	€ -	€ -	€ -	€ 2,321.28	€ -	€ -	€ -	€ -	€ -
	EWYQ-F-XR 180	€ -	€ -	€ -	€ -	€ -	€ 1,602.45	€ -	€ -	€ -	€ -	€ 1,602.45	€ -	€ -	€ -	€ -	€ 1,602.45	€ -	€ -	€ -	€ -	€ -
	Total Ex. Mainteinence	**€ -**	**€ -**	**€ -**	**€ -**	**€ -**	**€ 3,923.73**	**€ -**	**€ -**	**€ -**	**€ -**	**€ 3,923.73**	**€ -**	**€ -**	**€ -**	**€ -**	**€ 3,923.73**	**€ -**	**€ -**	**€ -**	**€ -**	**€ -**
Savage Value	EWYQ-G-XS160	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ 7,034.18
	EWYQ-F-XR 180	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ 4,855.91
	Total Savage Value	**€ -**	**€ -**	**€ -**	**€ -**	**€ -**	**€ -**	**€ -**	**€ -**	**€ -**	**€ -**	**€ -**	**€ -**	**€ -**	**€ -**	**€ -**	**€ -**	**€ -**	**€ -**	**€ -**	**€ -**	**€ 11,890.09**
Total Cost	**Grand Total**	**€ 222,344.70**	**€ 25,153.66**	**€ 25,771.49**	**€ 26,404.68**	**€ 27,053.61**	**€ 31,642.41**	**€ 28,400.30**	**€ 29,098.88**	**€ 29,814.85**	**€ 30,548.65**	**€ 35,224.45**	**€ 32,071.52**	**€ 32,861.52**	**€ 33,671.22**	**€ 34,501.09**	**€ 39,275.39**	**€ 36,223.44**	**€ 37,116.97**	**€ 38,032.79**	**€ 38,971.46**	**€ 28,043.48**
PV	**PV Total Cost**	**€ 222,344.70**	**€ 24,872.60**	**€ 25,198.78**	**€ 25,529.41**	**€ 25,864.56**	**€ 29,913.66**	**€ 26,548.68**	**€ 26,897.77**	**€ 27,251.64**	**€ 27,610.35**	**€ 31,480.68**	**€ 28,342.58**	**€ 28,716.24**	**€ 29,095.02**	**€ 29,479.00**	**€ 33,183.36**	**€ 30,262.83**	**€ 30,662.84**	**€ 31,068.34**	**€ 31,479.41**	**€ 22,399.16**

Table A. 8: Faro's LCCA

Item	Model	FY18	FY19	FY20	FY21	FY22	FY23	FY24	FY25	FY26	FY27	FY28	FY29	FY30	FY31	FY32	FY33	FY34	FY35	FY36	FY37	FY38
Installation Cost	EWYQ-G-XS120	€ 55,663.10	**€ -**	**€ -**	**€ -**	**€ -**	**€ -**	**€ -**	**€ -**	**€ -**	**€ -**	**€ -**	**€ -**	**€ -**	**€ -**	**€ -**	**€ -**	**€ -**	**€ -**	**€ -**	**€ -**	**€ -**
	EWYQ-G-XS085	€ 43,693.40	**€ -**	**€ -**	**€ -**	**€ -**	**€ -**	**€ -**	**€ -**	**€ -**	**€ -**	**€ -**	**€ -**	**€ -**	**€ -**	**€ -**	**€ -**	**€ -**	**€ -**	**€ -**	**€ -**	**€ -**
	Total Installation Cost	**€ 99,356.50**	**€ -**	**€ -**	**€ -**	**€ -**	**€ -**	**€ -**	**€ -**	**€ -**	**€ -**	**€ -**	**€ -**	**€ -**	**€ -**	**€ -**	**€ -**	**€ -**	**€ -**	**€ -**	**€ -**	**€ -**
Energy	EWYQ-G-XS120	€ -	€ 2,531.38	€ 2,597.61	€ 2,665.58	€ 2,735.32	€ 2,806.89	€ 2,880.33	€ 2,955.70	€ 3,033.03	€ 3,112.39	€ 3,193.83	€ 3,277.40	€ 3,363.15	€ 3,451.15	€ 3,541.44	€ 3,634.11	€ 3,729.19	€ 3,826.77	€ 3,926.89	€ 4,029.64	€ 4,135.08
	EWYQ-G-XS085	€ -	€ 1,761.68	€ 1,807.77	€ 1,855.07	€ 1,903.61	€ 1,953.42	€ 2,004.53	€ 2,056.98	€ 2,110.80	€ 2,166.03	€ 2,222.70	€ 2,280.86	€ 2,340.54	€ 2,401.78	€ 2,464.62	€ 2,529.11	€ 2,595.28	€ 2,663.19	€ 2,732.87	€ 2,804.38	€ 2,877.75
	Total Energy	**€ -**	**€ 4,293.06**	**€ 4,405.38**	**€ 4,520.65**	**€ 4,638.93**	**€ 4,760.31**	**€ 4,884.87**	**€ 5,012.68**	**€ 5,143.84**	**€ 5,278.42**	**€ 5,416.53**	**€ 5,558.26**	**€ 5,703.69**	**€ 5,852.93**	**€ 6,006.07**	**€ 6,163.22**	**€ 6,324.48**	**€ 6,489.96**	**€ 6,659.77**	**€ 6,834.02**	**€ 7,012.83**
O&M	EWYQ-G-XS120	€ -	€ 1,637.15	€ 1,669.89	€ 1,703.29	€ 1,737.36	€ 1,772.10	€ 1,807.55	€ 1,843.70	€ 1,880.57	€ 1,918.18	€ 1,956.55	€ 1,995.68	€ 2,035.59	€ 2,076.30	€ 2,117.83	€ 2,160.18	€ 2,203.39	€ 2,247.46	€ 2,292.41	€ 2,338.25	€ 2,385.02
	EWYQ-G-XS085	€ -	€ 1,285.10	€ 1,310.80	€ 1,337.02	€ 1,363.76	€ 1,391.03	€ 1,418.85	€ 1,447.23	€ 1,476.18	€ 1,505.70	€ 1,535.81	€ 1,566.53	€ 1,597.86	€ 1,629.82	€ 1,662.41	€ 1,695.66	€ 1,729.58	€ 1,764.17	€ 1,799.45	€ 1,835.44	€ 1,872.15
	Total O&M	€ -	**€ 2,922.25**	**€ 2,980.70**	**€ 3,040.31**	**€ 3,101.12**	**€ 3,163.14**	**€ 3,226.40**	**€ 3,290.93**	**€ 3,356.75**	**€ 3,423.88**	**€ 3,492.36**	**€ 3,562.21**	**€ 3,633.45**	**€ 3,706.12**	**€ 3,780.24**	**€ 3,855.85**	**€ 3,932.96**	**€ 4,011.62**	**€ 4,091.86**	**€ 4,173.69**	**€ 4,257.17**
Ex. Mainteinence	EWYQ-G-XS120	€ -	€ -	€ -	€ -	€ -	€ 982.29	€ -	€ -	€ -	€ -	€ 982.29	€ -	€ -	€ -	€ -	€ 982.29	€ -	€ -	€ -	€ -	€ -
	EWYQ-G-XS085	€ -	€ -	€ -	€ -	€ -	€ 771.06	€ -	€ -	€ -	€ -	€ 771.06	€ -	€ -	€ -	€ -	€ 771.06	€ -	€ -	€ -	€ -	€ -
	Total Ex. Mainteinence	**€ -**	**€ -**	**€ -**	**€ -**	**€ -**	**€ 1,753.35**	**€ -**	**€ -**	**€ -**	**€ -**	**€ 1,753.35**	**€ -**	**€ -**	**€ -**	**€ -**	**€ 1,753.35**	**€ -**	**€ -**	**€ -**	**€ -**	**€ -**
Savage Value	EWYQ-G-XS120	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ 2,976.64
	EWYQ-G-XS085	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ 2,336.55
	Total Savage Value	**€ -**	**€ -**	**€ -**	**€ -**	**€ -**	**€ -**	**€ -**	**€ -**	**€ -**	**€ -**	**€ -**	**€ -**	**€ -**	**€ -**	**€ -**	**€ -**	**€ -**	**€ -**	**€ -**	**€ -**	**€ 5,313.18**
Total Cost	**Grand Total**	**€ 99,356.50**	**€ 7,215.31**	**€ 7,386.08**	**€ 7,560.96**	**€ 7,740.05**	**€ 9,676.80**	**€ 8,111.27**	**€ 8,303.61**	**€ 8,500.58**	**€ 8,702.31**	**€ 10,662.24**	**€ 9,120.46**	**€ 9,337.14**	**€ 9,559.05**	**€ 9,786.31**	**€ 11,772.41**	**€ 10,257.44**	**€ 10,501.58**	**€ 10,751.62**	**€ 11,007.71**	**€ 5,956.82**
PV	**PV Total Cost**	**€ 99,356.50**	**€ 7,134.69**	**€ 7,221.94**	**€ 7,310.33**	**€ 7,399.86**	**€ 9,148.12**	**€ 7,582.43**	**€ 7,675.50**	**€ 7,769.78**	**€ 7,865.28**	**€ 9,529.03**	**€ 8,060.03**	**€ 8,159.32**	**€ 8,259.89**	**€ 8,361.78**	**€ 9,946.39**	**€ 8,569.57**	**€ 8,675.50**	**€ 8,782.82**	**€ 8,891.54**	**€ 4,757.89**

B ANNEX – ENERGY COST SAVING

Table B. 1: Penafiel's energy cost saving

Electricity Price (€/kWh)			0.11	0.11	0.12	0.12	0.12	0.12	0.12	0.12	0.13	0.13	0.13	0.13	0.13	0.14	0.14	0.14	0.14	0.14	0.15	0.15
Item	**Model**	**Type**	**FY20**	**FY21**	**FY22**	**FY23**	**FY24**	**FY25**	**FY26**	**FY27**	**FY28**	**FY29**	**FY30**	**FY31**	**FY32**	**FY33**	**FY34**	**FY35**	**FY36**	**FY37**	**FY38**	**FY39**
Energy Consumption (kWh/y)	MMY-MAP0802FT8 + n.a.	Old	39,222.20	39,653.64	40,089.83	40,530.82	40,976.66	41,427.40	41,883.11	42,343.82	42,809.60	43,280.51	43,756.59	44,237.92	44,724.53	45,216.50	45,713.88	46,216.74	46,725.12	47,239.10	47,758.73	48,284.07
	MMY-MAP0806FT8P-E + MMY-AP3016HT8P-E	New	38,563.43	38,987.62	39,416.49	39,850.07	40,288.42	40,731.59	41,179.64	41,632.62	42,090.57	42,553.57	43,021.66	43,494.90	43,973.34	44,457.05	44,946.08	45,440.48	45,940.33	46,445.67	46,956.57	47,473.10
	Total Energy Consumption Saving		**658.77**	**666.02**	**673.35**	**680.75**	**688.24**	**695.81**	**703.47**	**711.20**	**719.03**	**726.94**	**734.93**	**743.02**	**751.19**	**759.45**	**767.81**	**776.25**	**784.79**	**793.43**	**802.15**	**810.98**
Energy Saving Cost (€)	**Total Energy Cost Saving**		**73.98**	**75.92**	**77.90**	**79.94**	**82.03**	**84.18**	**86.38**	**88.64**	**90.96**	**93.34**	**95.78**	**98.29**	**100.86**	**103.50**	**106.21**	**108.99**	**111.84**	**114.76**	**117.77**	**120.85**
	Cumulative Energy Cost Saving		**73.98**	**149.90**	**227.80**	**307.74**	**389.77**	**473.95**	**560.33**	**648.97**	**739.93**	**833.27**	**929.06**	**1,027.35**	**1,128.21**	**1,231.71**	**1,337.92**	**1,446.90**	**1,558.74**	**1,673.51**	**1,791.27**	**1,912.12**

Table B. 2: Porto Building A's energy cost saving

Electricity Price (€/kWh)			0.11	0.11	0.12	0.12	0.12	0.12	0.12	0.12	0.13	0.13	0.13	0.13	0.13	0.14	0.14	0.14	0.14	0.14	0.15	0.15
Item	**Model**	**Type**	**FY20**	**FY21**	**FY22**	**FY23**	**FY24**	**FY25**	**FY26**	**FY27**	**FY28**	**FY29**	**FY30**	**FY31**	**FY32**	**FY33**	**FY34**	**FY35**	**FY36**	**FY37**	**FY38**	**FY39**
Energy Consumption (kWh/y)	EWYD360AJYNN-Q+EWAD190AJNVT+EWAD340AJNVT-QE	Old	449,259.00	454,200.85	459,197.06	464,248.23	469,354.96	474,517.86	479,737.56	485,014.67	490,349.83	495,743.68	501,196.86	506,710.03	512,283.84	517,918.96	523,616.07	529,375.84	535,198.98	541,086.17	547,038.11	553,055.53
	EWAD190TZ-PLB1+EWYD320-BZSS	New	447,695.96	452,620.61	457,599.44	462,633.04	467,722.00	472,866.94	478,068.48	483,327.23	488,643.83	494,018.91	499,453.12	504,947.10	510,501.52	516,117.04	521,794.33	527,534.06	533,336.94	539,203.64	545,134.89	551,131.37
	Total Energy Consumption Saving		**1,563.04**	**1,580.23**	**1,597.62**	**1,615.19**	**1,632.96**	**1,650.92**	**1,669.08**	**1,687.44**	**1,706.00**	**1,724.77**	**1,743.74**	**1,762.92**	**1,782.31**	**1,801.92**	**1,821.74**	**1,841.78**	**1,862.04**	**1,882.52**	**1,903.23**	**1,924.17**
Energy Saving Cost (€)	**Total Energy Saving Cost**		**175.53**	**180.12**	**184.84**	**189.67**	**194.63**	**199.73**	**204.95**	**210.32**	**215.82**	**221.46**	**227.26**	**233.21**	**239.31**	**245.57**	**251.99**	**258.59**	**265.35**	**272.30**	**279.42**	**286.73**
	Cumulative Energy Cost Saving		**175.53**	**355.65**	**540.49**	**730.16**	**924.79**	**1,124.52**	**1,329.47**	**1,539.79**	**1,755.60**	**1,977.07**	**2,204.33**	**2,437.54**	**2,676.84**	**2,922.41**	**3,174.41**	**3,432.99**	**3,698.35**	**3,970.64**	**4,250.07**	**4,536.80**

Table B. 3: Porto Building B's energy cost saving

Electricity Price (€/kWh)			0.11	0.11	0.12	0.12	0.12	0.12	0.12	0.12	0.13	0.13	0.13	0.13	0.13	0.14	0.14	0.14	0.14	0.14	0.15	0.15
Item	**Model**	**Type**	**FY20**	**FY21**	**FY22**	**FY23**	**FY24**	**FY25**	**FY26**	**FY27**	**FY28**	**FY29**	**FY30**	**FY31**	**FY32**	**FY33**	**FY34**	**FY35**	**FY36**	**FY37**	**FY38**	**FY39**
Energy Consumption (kWh/y)	EWAD210E-SL002+EQYD320DZ-SL003	Old	851,053.06	860,414.64	869,879.20	879,447.88	889,121.80	898,902.14	908,790.07	918,786.76	928,893.41	939,111.24	949,441.46	959,885.32	970,444.06	981,118.94	991,911.25	1,002,822.27	1,013,853.32	1,025,005.71	1,036,280.77	1,047,679.86
	EWAD220TZ-PL B1+EWYD320-BZSL	New	798,064.53	806,843.24	815,718.52	824,691.42	833,763.03	842,934.42	852,206.70	861,580.98	871,058.37	880,640.01	890,327.05	900,120.65	910,021.97	920,032.21	930,152.57	940,384.25	950,728.47	961,186.49	971,759.54	982,448.89
	Total Energy Consumption Saving		52,988.53	53,571.40	54,160.68	54,756.45	55,358.77	55,967.72	56,583.36	57,205.78	57,835.05	58,471.23	59,114.41	59,764.67	60,422.08	61,086.73	61,758.68	62,438.03	63,124.84	63,819.22	64,521.23	65,230.96
Energy Saving Cost (€)	Total Energy Cost Saving		5,950.61	6,106.31	6,266.08	6,430.03	6,598.27	6,770.92	6,948.08	7,129.88	7,316.43	7,507.86	7,704.31	7,905.89	8,112.75	8,325.02	8,542.84	8,766.37	8,995.74	9,231.11	9,472.64	9,720.49
	Cumulative Energy Cost Saving		5,950.61	12,056.92	18,323.00	24,753.03	31,351.31	38,122.23	45,070.31	52,200.18	59,516.61	67,024.48	74,728.78	82,634.67	90,747.42	99,072.44	107,615.28	116,381.64	125,377.38	134,608.49	144,081.13	153,801.63
Energy Consumption (kWh/y)	EWAD210E-SL002	Old	287,567.66	290,730.90	293,928.94	297,162.16	300,430.95	303,735.69	307,076.78	310,454.62	313,869.62	317,322.19	320,812.73	324,341.67	327,909.43	331,516.44	335,163.12	338,849.91	342,577.26	346,345.61	350,155.41	354,007.12
	EWAD220TZ-PL B1	New	239,908.97	242,547.97	245,216.00	247,913.38	250,640.42	253,397.47	256,184.84	259,002.87	261,851.91	264,732.28	267,644.33	270,588.42	273,564.89	276,574.11	279,616.42	282,692.20	285,801.82	288,945.64	292,124.04	295,337.40
	Total Energy Consumption Saving		47,658.69	48,182.93	48,712.94	49,248.79	49,790.52	50,338.22	50,891.94	51,451.75	52,017.72	52,589.91	53,168.40	53,753.26	54,344.54	54,942.33	55,546.70	56,157.71	56,775.44	57,399.97	58,031.37	58,669.72
Energy Saving Cost (€)	Total Energy Cost Saving		5,352.07	5,492.11	5,635.81	5,783.27	5,934.59	6,089.87	6,249.21	6,412.72	6,580.51	6,752.69	6,929.37	7,110.68	7,296.73	7,487.65	7,683.56	7,884.60	8,090.90	8,302.60	8,519.84	8,742.76
	Cumulative Energy Cost Saving		5,352.07	10,844.18	16,479.99	22,263.26	28,197.84	34,287.71	40,536.92	46,949.64	53,530.15	60,282.83	67,212.20	74,322.88	81,619.61	89,107.26	96,790.82	104,675.42	112,766.32	121,068.92	129,588.76	138,331.52

Table B. 4: Guarda's energy cost saving

Electricity Price (€/kWh)			0.11	0.11	0.12	0.12	0.12	0.12	0.12	0.12	0.13	0.13	0.13	0.13	0.13	0.14	0.14	0.14	0.14	0.14	0.15	0.15
Item	**Model**	**Type**	**FY20**	**FY21**	**FY22**	**FY23**	**FY24**	**FY25**	**FY26**	**FY27**	**FY28**	**FY29**	**FY30**	**FY31**	**FY32**	**FY33**	**FY34**	**FY35**	**FY36**	**FY37**	**FY38**	**FY39**
Energy Consumption (kWh/y)	MMY-MAP0802FT8+MMY-MAP1002FT8-E	Old	19,869.00	20,087.56	20,308.52	20,531.92	20,757.77	20,986.10	21,216.95	21,450.34	21,686.29	21,924.84	22,166.01	22,409.84	22,656.35	22,905.57	23,157.53	23,412.26	23,669.80	23,930.16	24,193.39	24,459.52
	MMY-MAP0806FT8P-E+MMY-MAP1006FT8P-E	New	18,985.96	19,194.80	19,405.95	19,619.41	19,835.23	20,053.41	20,274.00	20,497.01	20,722.48	20,950.43	21,180.88	21,413.87	21,649.43	21,887.57	22,128.33	22,371.74	22,617.83	22,866.63	23,118.16	23,372.46
	Total Energy Consumption Saving		**883.04**	**892.76**	**902.58**	**912.50**	**922.54**	**932.69**	**942.95**	**953.32**	**963.81**	**974.41**	**985.13**	**995.96**	**1,006.92**	**1,018.00**	**1,029.19**	**1,040.52**	**1,051.96**	**1,063.53**	**1,075.23**	**1,087.06**
Energy Saving Cost (€)	**Total Energy Cost Saving**		**99.17**	**101.76**	**104.42**	**107.16**	**109.96**	**112.84**	**115.79**	**118.82**	**121.93**	**125.12**	**128.39**	**131.75**	**135.20**	**138.73**	**142.36**	**146.09**	**149.91**	**153.83**	**157.86**	**161.99**
	Cumulative Energy Cost Saving		**99.17**	**200.93**	**305.35**	**412.50**	**522.46**	**635.30**	**751.09**	**869.90**	**991.83**	**1,116.95**	**1,245.34**	**1,377.09**	**1,512.29**	**1,651.02**	**1,793.38**	**1,939.47**	**2,089.39**	**2,243.22**	**2,401.08**	**2,563.07**

Table B. 5: Coimbra's energy cost saving

Electricity Price (€/kWh)			0.11	0.11	0.12	0.12	0.12	0.12	0.12	0.12	0.13	0.13	0.13	0.13	0.13	0.14	0.14	0.14	0.14	0.14	0.15	0.15
Item	**Model**	**Type**	**FY20**	**FY21**	**FY22**	**FY23**	**FY24**	**FY25**	**FY26**	**FY27**	**FY28**	**FY29**	**FY30**	**FY31**	**FY32**	**FY33**	**FY34**	**FY35**	**FY36**	**FY37**	**FY38**	**FY39**
Energy Consumption (kWh/y)	GW-1335-G0	Old	204,057.30	206,301.93	208,571.25	210,865.54	213,185.06	215,530.09	217,900.92	220,297.83	222,721.11	225,171.04	227,647.92	230,152.05	232,683.72	235,243.24	237,830.92	240,447.06	243,091.98	245,765.99	248,469.41	251,202.58
	EWYQ-G-XS120	New	188,212.76	190,283.10	192,376.22	194,492.36	196,631.77	198,794.72	200,981.46	203,192.26	205,427.38	207,687.08	209,971.63	212,281.32	214,616.42	216,977.20	219,363.95	221,776.95	224,216.50	226,682.88	229,176.39	231,697.33
	Total Energy Consumption Saving		**15,844.54**	**16,018.83**	**16,195.03**	**16,373.18**	**16,553.28**	**16,735.37**	**16,919.46**	**17,105.57**	**17,293.73**	**17,483.96**	**17,676.29**	**17,870.73**	**18,067.31**	**18,266.05**	**18,466.97**	**18,670.11**	**18,875.48**	**19,083.11**	**19,293.02**	**19,505.25**
Energy Saving Cost (€)	**Total Energy Cost Saving**		**1,779.34**	**1,825.90**	**1,873.67**	**1,922.70**	**1,973.00**	**2,024.63**	**2,077.60**	**2,131.96**	**2,187.75**	**2,244.99**	**2,303.73**	**2,364.01**	**2,425.86**	**2,489.33**	**2,554.47**	**2,621.30**	**2,689.89**	**2,760.27**	**2,832.49**	**2,906.61**
	Cumulative Energy Cost Saving		**1,779.34**	**3,605.24**	**5,478.91**	**7,401.61**	**9,374.61**	**11,399.24**	**13,476.84**	**15,608.81**	**17,796.55**	**20,041.54**	**22,345.27**	**24,709.27**	**27,135.13**	**29,624.47**	**32,178.93**	**34,800.23**	**37,490.12**	**40,250.39**	**43,082.89**	**45,989.49**

Table B. 6: Lisbon Building B's energy cost saving

Electricity Price (€/kWh)			0.11	0.11	0.12	0.12	0.12	0.12	0.12	0.12	0.13	0.13	0.13	0.13	0.13	0.14	0.14	0.14	0.14	0.14	0.15	0.15
Item	**Model**	**Type**	**FY20**	**FY21**	**FY22**	**FY23**	**FY24**	**FY25**	**FY26**	**FY27**	**FY28**	**FY29**	**FY30**	**FY31**	**FY32**	**FY33**	**FY34**	**FY35**	**FY36**	**FY37**	**FY38**	**FY39**
Energy Consumption (kWh/y)	SME 1202 +HPAN/SL 1004	Old	234,427.00	237,005.70	239,612.76	242,248.50	244,913.23	247,607.28	250,330.96	253,084.60	255,868.53	258,683.08	261,528.60	264,405.41	267,313.87	270,254.32	273,227.12	276,232.62	279,271.18	282,343.16	285,448.94	288,588.88
	NECS-W/B 1104+NECS-Q/B0904	New	159,205.28	160,956.53	162,727.06	164,517.05	166,326.74	168,156.33	170,006.05	171,876.12	173,766.76	175,678.19	177,610.65	179,564.37	181,539.58	183,536.51	185,555.42	187,596.52	189,660.09	191,746.35	193,855.56	195,987.97
	Total Energy Consumption Saving		**75,221.72**	**76,049.16**	**76,885.70**	**77,731.45**	**78,586.49**	**79,450.94**	**80,324.90**	**81,208.48**	**82,101.77**	**83,004.89**	**83,917.95**	**84,841.04**	**85,774.29**	**86,717.81**	**87,671.71**	**88,636.10**	**89,611.09**	**90,596.81**	**91,593.38**	**92,600.91**
Energy Saving Cost (€)	**Total Energy Cost Saving**		**8,447.40**	**8,668.43**	**8,895.24**	**9,127.98**	**9,366.81**	**9,611.90**	**9,863.39**	**10,121.47**	**10,386.29**	**10,658.05**	**10,936.92**	**11,223.08**	**11,516.74**	**11,818.07**	**12,127.29**	**12,444.60**	**12,770.21**	**13,104.35**	**13,447.22**	**13,799.07**
	Cumulative Energy Cost Saving		**8,447.40**	**17,115.83**	**26,011.06**	**35,139.04**	**44,505.85**	**54,117.75**	**63,981.14**	**74,102.60**	**84,488.90**	**95,146.95**	**106,083.87**	**117,306.95**	**128,823.69**	**140,641.76**	**152,769.05**	**165,213.65**	**177,983.87**	**191,088.22**	**204,535.44**	**218,334.51**

Table B. 7: Lisbon Building C's energy cost saving

Electricity Price (€/kWh)			0.11	0.11	0.12	0.12	0.12	0.12	0.12	0.12	0.13	0.13	0.13	0.13	0.13	0.14	0.14	0.14	0.14	0.14	0.15	0.15
Item	**Model**	**Type**	**FY20**	**FY21**	**FY22**	**FY23**	**FY24**	**FY25**	**FY26**	**FY27**	**FY28**	**FY29**	**FY30**	**FY31**	**FY32**	**FY33**	**FY34**	**FY35**	**FY36**	**FY37**	**FY38**	**FY39**
Energy Consumption (kWh/y)	EUWY N070CZ6YL+EWYQ 180DAYNN	Old	179,795.76	181,773.51	183,773.02	185,794.53	187,838.27	189,904.49	191,993.44	194,105.36	196,240.52	198,399.17	200,581.56	202,787.96	205,018.62	207,273.83	209,553.84	211,858.93	214,189.38	216,545.46	218,927.46	221,335.67
	EWYQ-G-XS160+EWYQ-F-XR 180	New	165,753.41	167,576.70	169,420.04	171,283.66	173,167.78	175,072.63	176,998.43	178,945.41	180,913.81	182,903.86	184,915.80	186,949.88	189,006.32	191,085.39	193,187.33	195,312.39	197,460.83	199,632.90	201,828.86	204,048.98
	Total Energy Consumption Saving		**14,042.35**	**14,196.82**	**14,352.98**	**14,510.86**	**14,670.48**	**14,831.86**	**14,995.01**	**15,159.95**	**15,326.71**	**15,495.31**	**15,665.76**	**15,838.08**	**16,012.30**	**16,188.43**	**16,366.51**	**16,546.54**	**16,728.55**	**16,912.56**	**17,098.60**	**17,286.69**
Energy Saving Cost (€)	**Total Energy Cost Saving**		**1,576.96**	**1,618.22**	**1,660.56**	**1,704.01**	**1,748.59**	**1,794.34**	**1,841.29**	**1,889.47**	**1,938.91**	**1,989.64**	**2,041.70**	**2,095.12**	**2,149.94**	**2,206.19**	**2,263.92**	**2,323.15**	**2,383.94**	**2,446.31**	**2,510.32**	**2,576.00**
	Cumulative Energy Cost Saving		**1,576.96**	**3,195.17**	**4,855.73**	**6,559.74**	**8,308.33**	**10,102.67**	**11,943.96**	**13,833.43**	**15,772.34**	**17,761.98**	**19,803.68**	**21,898.80**	**24,048.74**	**26,254.93**	**28,518.84**	**30,842.00**	**33,225.93**	**35,672.25**	**38,182.57**	**40,758.57**

Table B. 8: Faro's energy cost saving

Electricity Price (€/kWh)			0.11	0.11	0.12	0.12	0.12	0.12	0.12	0.12	0.13	0.13	0.13	0.13	0.13	0.14	0.14	0.14	0.14	0.14	0.15	0.15
Item	**Model**	**Type**	**FY20**	**FY21**	**FY22**	**FY23**	**FY24**	**FY25**	**FY26**	**FY27**	**FY28**	**FY29**	**FY30**	**FY31**	**FY32**	**FY33**	**FY34**	**FY35**	**FY36**	**FY37**	**FY38**	**FY39**
Energy Consumption (kWh/y)	EWYD130DAYN + EWYD100DAYN	Old	41,636.00	42,094.00	42,557.03	43,025.16	43,498.43	43,976.92	44,460.66	44,949.73	45,444.18	45,944.06	46,449.45	46,960.39	47,476.96	47,999.20	48,527.19	49,060.99	49,600.66	50,146.27	50,697.88	51,255.56
	EWYQ-G-XS120 + EWYQ-G-XS085	New	38,228.47	38,648.98	39,074.12	39,503.94	39,938.48	40,377.80	40,821.96	41,271.00	41,724.98	42,183.96	42,647.98	43,117.11	43,591.40	44,070.90	44,555.68	45,045.79	45,541.30	46,042.25	46,548.72	47,060.75
	Total Energy Consumption Saving		**3,407.53**	**3,445.01**	**3,482.91**	**3,521.22**	**3,559.95**	**3,599.11**	**3,638.70**	**3,678.73**	**3,719.20**	**3,760.11**	**3,801.47**	**3,843.28**	**3,885.56**	**3,928.30**	**3,971.51**	**4,015.20**	**4,059.37**	**4,104.02**	**4,149.16**	**4,194.80**
Energy Saving Cost (€)	**Total Energy Saving Cost**		**382.67**	**392.68**	**402.95**	**413.50**	**424.31**	**435.42**	**446.81**	**458.50**	**470.50**	**482.81**	**495.44**	**508.40**	**521.71**	**535.36**	**549.36**	**563.74**	**578.49**	**593.62**	**609.16**	**625.10**
	Cumulative Energy Cost Saving		**382.67**	**775.34**	**1,178.30**	**1,591.79**	**2,016.11**	**2,451.52**	**2,898.33**	**3,356.83**	**3,827.33**	**4,310.14**	**4,805.58**	**5,313.98**	**5,835.69**	**6,371.05**	**6,920.41**	**7,484.15**	**8,062.64**	**8,656.26**	**9,265.42**	**9,890.51**