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CATALOGUE OF ACTIVE AND PASSIVE SOLUTIONS FOR THE CONSTRUCTION OF THERMAL AUTONOMOUS HOUSING

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RESUMO

Esta investigação visa esclarecer as diferentes soluções disponíveis para o desenvolvimento de casas termicamente autónomas, bem como o grau de poupança de cada uma das soluções.

Os estudos existentes têm-se centrado em soluções ativas e passivas separadas, este estudo converte os conhecimentos disponíveis num catálogo para revelar uma comparação direta entre diferentes soluções em termos de desempenho de poupança de energia e retorno económico do investimento.

No final, esta tese contribui para o conhecimento existente em torno de edifícios termicamente autónomos e esclarece uma análise simplificada das diferentes soluções atualmente disponíveis. São apresentados os diferentes aspetos a ter em conta na escolha de investir numa solução ativa ou passiva. É fornecida e organizada uma comparação com base na poupança de energia e no retorno do investimento. Compreender os resultados de cada solução é crucial para uma tomada de decisão informada, uma vez que os proprietários têm capacidade de investimento limitada.

PALAVRAS-CHAVE: Catálogo, Eficiência Energética, Certificação Energética, Passivas, Ativas

ABSTRACT

This research aims to enlighten the different solutions available to the development of thermal autonomous houses as well as the degree of saving of each of the solutions.

Existing studies have focused on separate active and passive solutions, this study converts the knowledge available into a catalogue to reveal a direct comparison between different solutions in terms of energy saving performance and economic return on investment.

In the end, this thesis contributes to the existing knowledge around thermal autonomous housing and enlightens a simplified analysis of the different solutions currently available. The different aspects to be considering when choosing to invest in an active or passive solution are presented. A comparison based on energy saving and return on investment is provided and organized to the respective technical data sheet. Understanding the outcomes of each solution is crucial for an informed decision making since owners have limited investment capability.

KEYWORDS: Catalogue, Energy Efficiency, Energy Certification, Passive, Active

ACKNOWLEDGMENTS

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1 INTRODUCTION

1.1. FRAMING AND PRESENTATION OF THE WORK

The residential construction sector disproportionate evolution in the last half of the 20th century, guided the Portuguese modern housing standards to the absolute need for a turning point on the beginning of the new century. As described by the Portuguese national institute of statistics, the INE, on a study published in 2011, the growth of the housing stock in the last 50 years was disproportionate in relation to the demographic growth. Also, the alliance of these factors with the several periods of economic crisis, lead the Portuguese standards for quality in construction to decline due to the growing search for affordable housing. Additionally, the same study registered that almost 17% of the national housing stock was in need of medium to extensive repairment work, that was largely caused by the over accumulation of debt in Portuguese households during this period. As a consequence, in 2014, the BPIE (Building Performance Institute Europe) conducted an in-depth study and concluded that Portugal is in second place in the EU in the Excess winter deaths index (EWDI). The same study reveals that in the year 2012, 43% of the Portuguese population did not have the financial capacity to have the minimum conditions of thermal comfort (BPIE, 2014). The result of this study summarizes the problem in Portuguese households: even though Portugal has a temperate and very favourable climate, the thermal performance of the typical residential building is very underwhelming, resulting in the need for over expenses in heating and cooling necessities.

As a direct result of the extreme reliance on heating and cooling devices, the energy consumption in households continues to rise, on an unsustainable tendency, as well as the environmental issues related to the greenhouse gases emissions.

All of the previously stated motives incite a need for the change of mentality on the construction sector, in the direction of the incentive to extensive renovation works and the promotion of the diffusion of knowledge on energy efficient buildings.

The concept of building efficiency is, in fact, a fresh idea in the Portuguese building sector and it was only strengthened since the European Union (EU) drafted the Energy Performance of Buildings Directive (Directive 2002/91/EC) which forced the renovation of Portuguese building regulations. This European directive enforces the development of strategies towards long term rehabilitation, confronting the expected energy crisis with more energy efficient housing and the increased preference for renewable energy sources in the hopes of reaching de decarbonization of the building stock, following Portugal's Roadmap for Carbon Neutrality 2050 (RCN 2050).

All of these new ambitious goals and legislations turned the market and the construction sector to the research of different solutions. Autonomous housing is a growing concept that contemplates solutions to the appointed problems in a very sustainable factor. The two most diffused interpretations of this concept are the Passive House and the net-zero energy buildings (nZEB) models, that envision two different approaches. In the first one the energy necessities of a building are mitigated through the implementation of solutions that ensure a strong thermal performance of the building fabric, while in the other model the approach consists of matching the characteristic needs of the building with the production of electric energy.

The growing market on construction solutions, and the technologic development in the renewable energy sources area, implicates the need for technical documents that assemble the existing systems with easily interpretable information. This is the main objective of this thesis. The researched systems were organized and detailed in technical data sheets, facilitating the readers assimilation of the performance behaviour and the level of expected feasibility of the general solution. Also, a brief economic study was pursued in order to attain a succinct feasibility assessment of each explored system, with the aid of the spreadsheet developed by ITECONS, that facilitates the results of the energy balance of a base model hypothetical building, through the methodology envisioned in the national energy certification system, the SCE.

1.2. OBJECTIVES

When planning the construction of a house, the extensive list of manufacturers, solutions, systems, and configurations to match the necessities around thermal autonomous housing, a variety of available solutions are considered. Previous studies have investigated the current available options, providing relevant information to help the knowledge around each of the options and hence, supporting the decision making. However, that information is disperse and not easily accessible. This study provides a catalogue that gathers all relevant information around each option, to reveal a direct comparison between different solutions. Also, this study provides a comparison between different solutions to help decision making. This comparison is made based on energy saving performance and economic return on investment.

1.3. ORGANIZATION OF THE THESIS

The thesis is divided into 5 chapters. First, there is an introduction to the topic in the context of the current Portuguese framework. The climate, energy consumption and current legislation on housing's energy performance is presented.

Then, an analysis on the Portuguese housing stocks is made, where the state of conservation of the building stock, construction standards and rehabilitation standards are highlighted. To complete the current picture of the Portuguese context, an explanation of the Portuguese energy certification system, the SCE, and the energy certification process is made, completed by complementary concepts and studies.

Next, the topic of autonomous housing is posited, and the concepts of the Passive house and net-zero energy building (nZEB) models are explored. Subsequently active and passive solutions for the construction of thermal autonomous housing currently available on the market are presented. The previous identified solutions are aggregated in a catalogue configuration. Methodology for this configuration is explained, elucidating on the structure of the technical data sheets and the economic assessment of the studied solutions, for a correct analysis of the catalogue.

Finally, conclusions are made to provide support for developers, project managers and owners to better assess what active and passive solutions better suit their need for the construction of thermal autonomous housing. Relevant comparisons in terms of energy savings and economic return are made. To finish, limitations of the present thesis are presented in order to provide the academia with future research suggestions that can enhance the present work.

2 ACTIVE AND PASSIVE SOLUTIONS IN BUILDINGS

2.1. CONTEXTUALIZATION OF THE PORTUGUESE CLIMATE, ENERGY CONSUMPTION AND LEGISLATION ON HOUSING ENERGY PERFORMANCE

2.1.1. PORTUGUESE CLIMATE

Portugal, located in the extreme south-west of the European mainland, can be generally characterized has having a temperate warm climate, significantly above the predominantly cold climates of other European countries. The Portuguese climate fits in the typical Mediterranean Climate, characterized by dry summers and mild wet winters, amongst countries like Spain, Italy, Greece, Cyprus, and Malta.

The Koppen-Geiger system is a climate classification system developed in 20th century by the climatologists Wladimir Koppen and Rudolf Greiger. The following map, **Figure 1** , describes the distribution of climates in Europe, through an adaptation of the previous system by (Peel et al., 2007) and based on collected data from 1209 precipitation and 684 temperature stations. Each climate type is represented with a capital letter, from "A" to "E", indicating, respectively, tropical climate and polar climate. The dominant climate type in Europe, by land area, is cold "D" (44,4%), followed by arid "B" (36,3%), temperate "C" (17%) and polar "E" (2,3%). The second and third letters in this classification are defined by local thermal and pluviometry particularities (Peel et al., 2007).

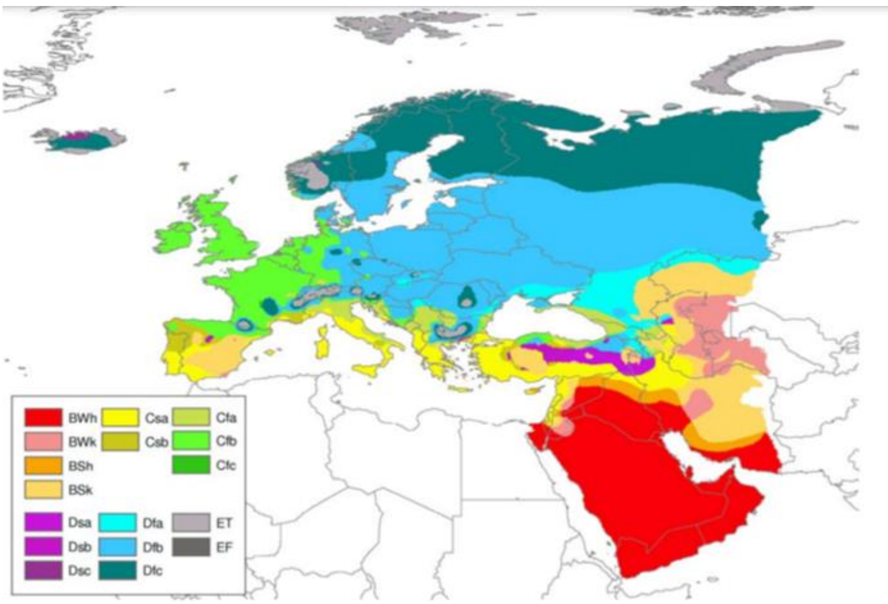

Figure 1 - Koppen-Geiger climate type map of Europe from (Peel et al., 2007)

Thus, Portugal's mainland climate is classified as temperate "C" and divided into two regions (**Figure 2**): one temperate climate region with rainy Winter and hot and dry Summer (Csa), and another temperate climate region with rainy Winter and warm and dry Summer (Csb).

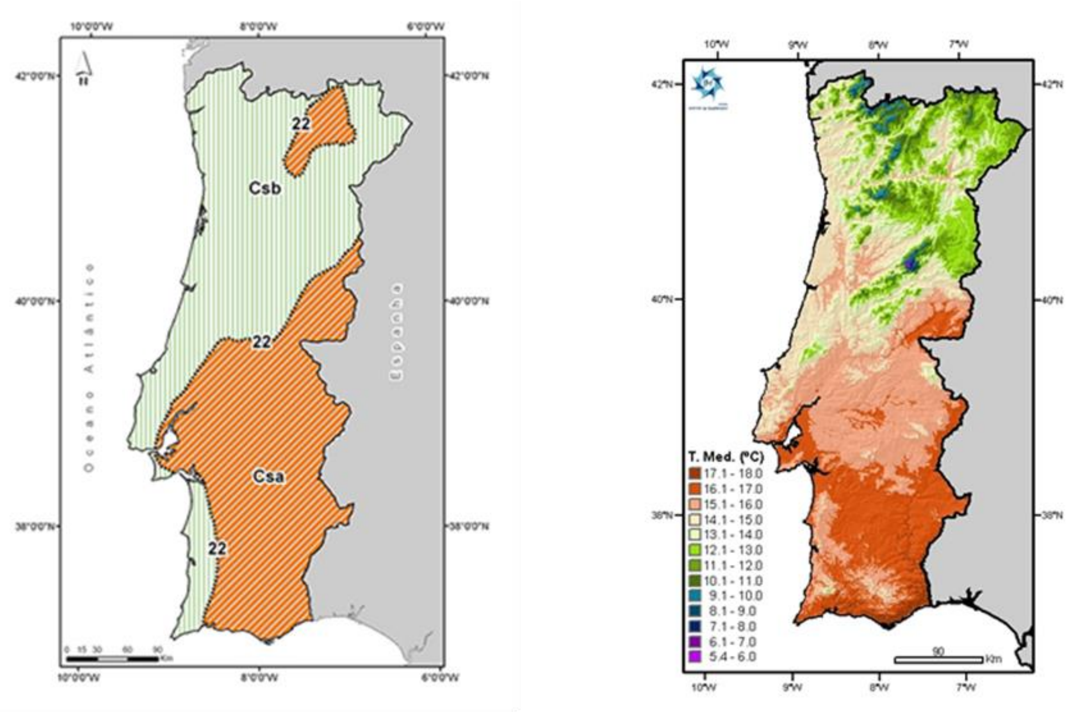

Figure 2 - Portuguese Climate following Kroppen-Geiger's classification and average yearly temperature in Portugal (IPMA website, 2021)

The average yearly temperature in Portugal is about 15,2ºC, contrasting with the European average of 9,45ºC (IMPA, 2021). Additionally, this yearly average temperature fluctuates in the Portuguese mainland, increasing from northern to southern regions. Hence, in the higher lands of the north the annual average temperature is about 7ºC while in the southern coastal regions it is about 18ºC (IMPA, 2021).

Heating degree days (HDD) is an indicator that contribute immensely to the calculation of a building's annual heating energy necessities. This is based on a methodology that assumes that in the cold season, a building will develop a series of equilibrium states, while external conditions, like wind velocity and air humidity, and interior conditions, mainly interior energy gains, remain constant. It relies on the base temperature, defined as the lowest daily mean air temperature not leading to indoor heating. The value of the base temperature depends in principle on several factors associated with the building and the surrounding environment[1] (Eurostat, 2021). Although, it is a relatively simple method it will output very acceptable data.

As it can be observed in **Figure 3**, Portugal's annual HDD is significantly lower than the average in EU. This strengthens the idea of low consuming heating energy requirements in Portugal due to its favourable climate.

[1] By using a general climatological approach, the base temperature is set to a constant value of 15°C in the HDD calculation. **If $Tm \leq 15°C$ Then [$HDD = \sum i(18°C - Tim)$] Else [$HDD = 0$]**, where Tim is the mean air temperature of day i.

Eurostat. (2021). Retrieved May from https://ec.europa.eu/eurostat/web/energy/data/database

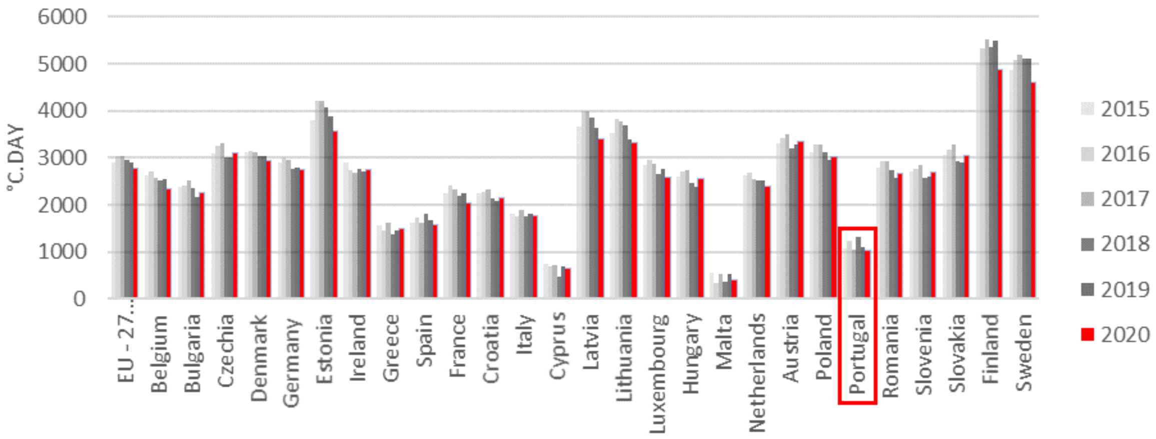

Figure 3 - Annual Heating Degree Days (HDD) by EU country, from 2015 to 2020 (EUROSTAT)

Cooling degree days (CDD) [2], which serves a similar purpose to HDD, is accountable for the calculation of cooling energy necessities in households. Most of the European countries have low results on this indicator mainly due to the typical cold climate and lower average temperatures throughout the year, so it is expected that the Mediterranean countries assume the high-top results.

As it can be observed in the chart on **Figure 4**, the expected outcome is mostly confirmed. Southern countries tend to have higher necessity in cooling spaces due to the higher average exterior temperatures felt in the cooling season. Hence, in most European countries, specifically those with extremely cold winters and modest summers, household energy consumption is significantly, and almost exclusively, impacted by elevated energy expenses in pursuance of adequate comfort levels throughout the year, while southern countries, with predominantly less severe winters and warm to hot summers, have the particular advantage of its climate being more compatible with human comfort indoors, with the exception of potential overheating.

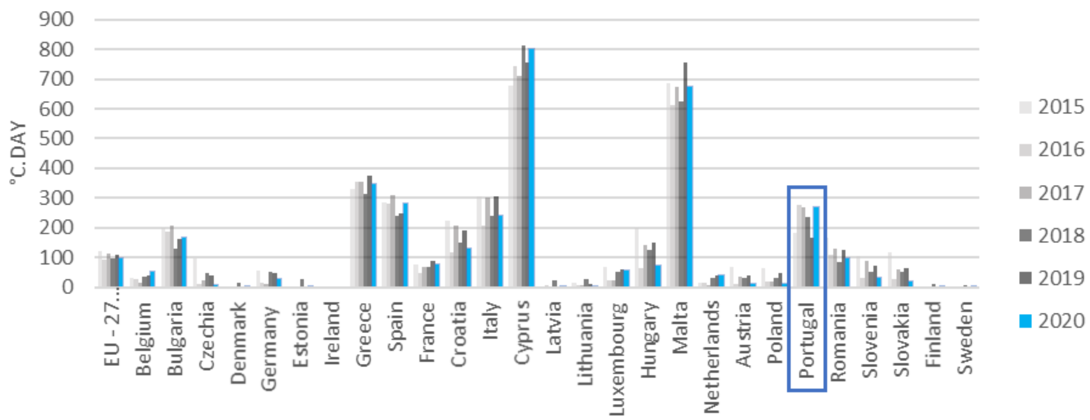

Figure 4 - Cooling Degree Days (CDD) by EU country, from 2015 to 2020 (EUROSTAT)

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[2] By using a general climatological approach, the base temperature is set to a constant value of 24°C in the CDD calculation. **If Tm ≥ 24°C Then [CDD = ∑iTim - 21°C)] Else [CDD = 0],** where Tim is the mean air temperature of day i. Ibid.

2.1.2. Portuguese energy consumption in the European context

In 2018, households represented 26% of final energy consumption, or 17% of gross inland energy consumption, in the EU (Eurostat, 2021).

As shown in **Figure 5**, the main use of energy by EU housing stock was for heating purposes, nearly 64% of total household energy expenses. The final energy consumption for space heating purposes in Portuguese households, in 2018, was 9,5 billion kWh (kilo-Watt hour), considerably below the European average of 75,3 billion kWh. This value amounts to a portion of about 28,2% of the total final energy consumption in the residential sector of the country in the same year, also very under the EU average. Regarding the energy needs for space cooling, the Portuguese housing stock consumed a total of 0,21 billion kWh in 2018, slightly below the EU average of 0,38 billion kWh. This amount represents 0,6% of the total final energy consumption in the residential sector of the country in the same year, which is marginally above the EU average of 0,4% (Eurostat, 2021).

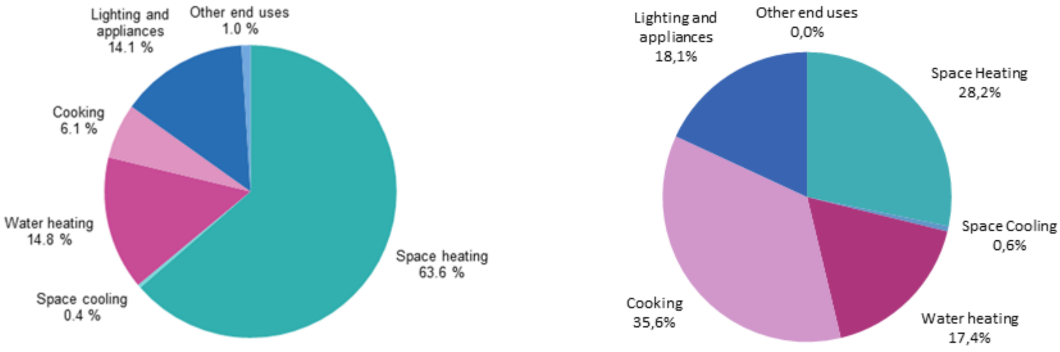


Figure 5 - Final energy consumption in the residential sector by use, EU-27 in the left and Portugal in the right, 2018 (Eurostat)

The following two charts, presented in **Figure 6** and **Figure 7**, represent the evolution of household consumption of energy, in order to achieve thermal comfort indoors, between the years 2000 and 2018. **Figure 6** focuses on the average heating energy consumption per dwellings in the EU, where it can be observed that Portuguese houses consumed an annual average of 0,137 *toe*[3] in 2018, considerably under the European average of 0,88 *toe*. It is worth mentioning that the general drop of consumption for heating purposes in the EU, about 1,3% per year in the referenced period, represents not only the value in the implementation of all the approved legislations and proposed goals and measures by the European Parliament in order to tackle the imminent energy crisis, but also the adoption of more efficient heating systems like gas condensing boilers, heat pumps and pellet boilers.

Air conditioning units gained swift popularity since the year 2000, representing a substantial increase in energy consumption at EU level, from 14 kWh/dwelling to 42 kWh/dwelling in 2018[4]. The Portuguese housing stock as also seen a growth in this area, from 48,2 kWh/dwelling to 52,6 kWh/dwelling in the reference period.

[3] *toe* (Tonne of oil equivalent) is an energy unit defined as the amount of energy released by burning one tonne of crude oil, which is approximately 42 gigajoules or 11 666,67 kWh.
[4] Average consumption per dwelling obtained by dividing the total consumption for air conditioning by the total number of dwellings, not only those with air conditioning.

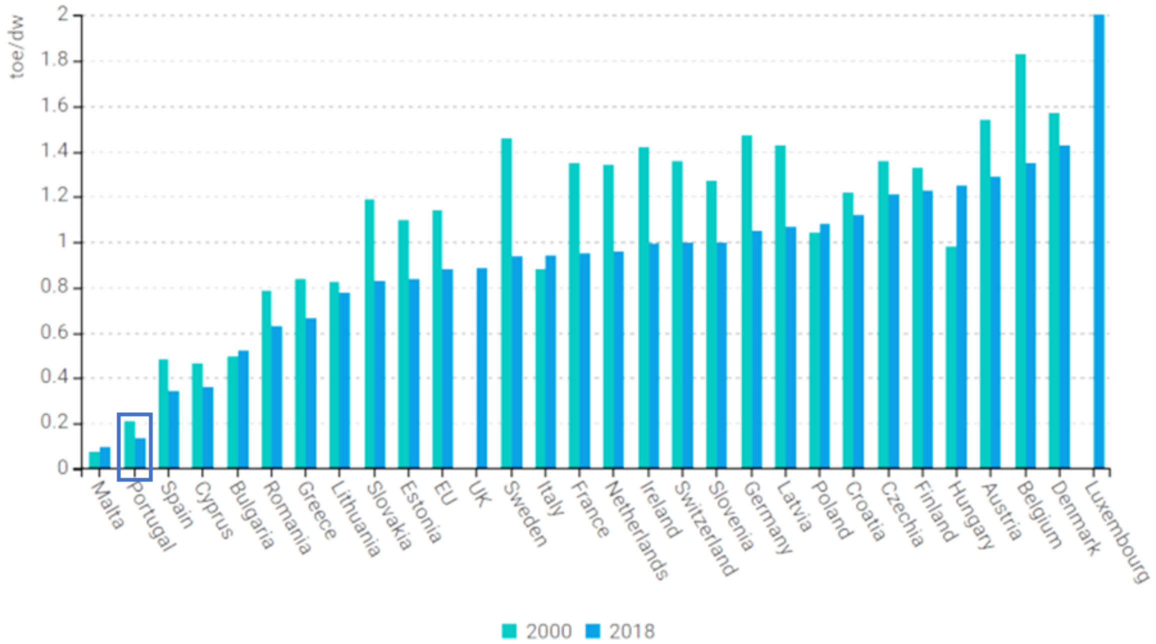


Figure 6 – Heating consumption per dwelling (Odyssee-Mure, 2018).

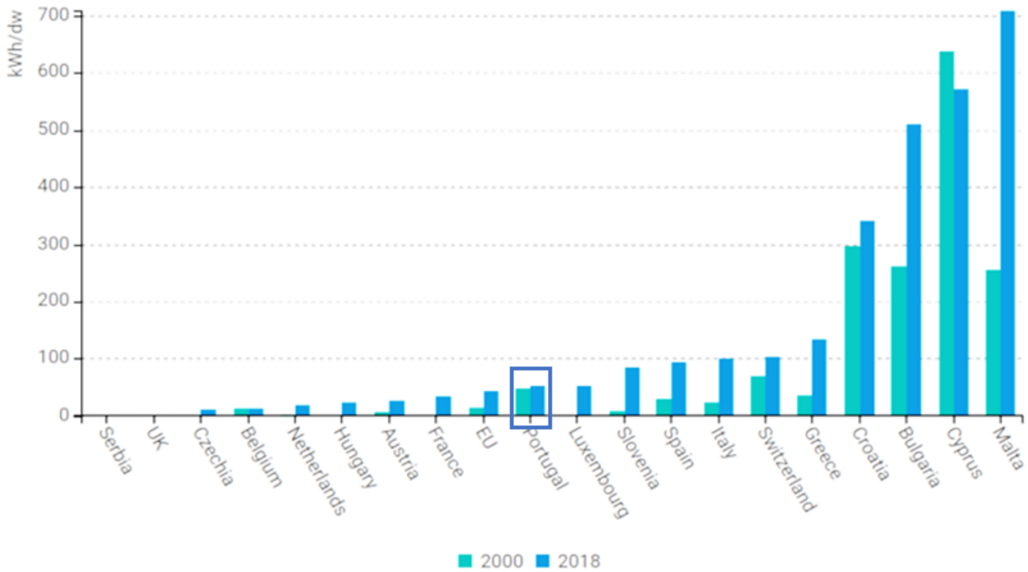


Figure 7 - Consumption of air conditioning per dwelling (Odyssee-Mure, 2018).

Having this brief perspective of the average expenses in the Portuguese residential sector, it should be interesting to understand the full scope of this subject, analysing the evolution of typical household consumption in relation to national energy consumption.

The evolution of primary and final energy consumption in Portugal, as shown in **Figure 8**, is essentially defined by three particular periods. First, the accentuated rise of national energy consumption, between 1995 and 2005. The next decade, 2005 to 2015, is marked by a significant drop of 16% of total energy consumption, result of both 2007-2008 and 2010-2014 financial crisis, the first being of global levels and the second a perpetuation on the Portuguese economy. The last period, corresponding to more modern times, is significantly influenced by the global investment on renewable energies, which in the Portuguese case represents 27% of total primary energy consumption by 2019, and the development of energy efficiency standards. By 2019, EU averages on primary and final energy consumptions are about 50 000 ktoe (kilo tonnes of oil equivalent) and 36 400 ktoe respectively, which are numbers far greater than the Portuguese results.

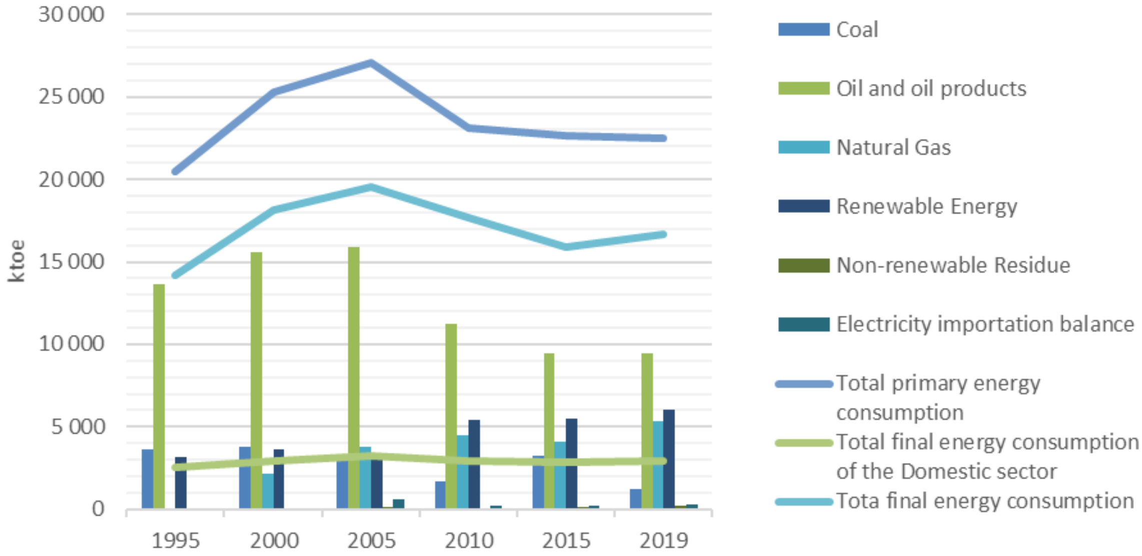


Figure 8 - Portugal's energy consumption data from 1995 to 2019 (DGEG, 2019)

Regarding the domestic sector, it has shown slight variation, rising about 13% by 2019 in reference to 1995 values. Additionally, in 2013, the Portuguese building stock represents a portion of 30% of the total final energy consumptions, accounting a portion of 17,4% for the domestic sector, while at EU level, these numbers are 40% and 26,7%, on the respective subjects (Directive 2010/31/EU, 2010) (DGEG, 2019)

Another relevant topic for this analysis is the energy dependency indicator, which shows that, even if the levels of energy consumption in Portugal, seen on previous observations, were very satisfying, this country has one of the highest results in this subject, revealing a dependency factor of about 80%, as shown in **Figure 9**, far greater to the European average of about 50%. This indicator translates the energy importation balance divided by the sum of the total primary energy consumption (DGEG, 2019).

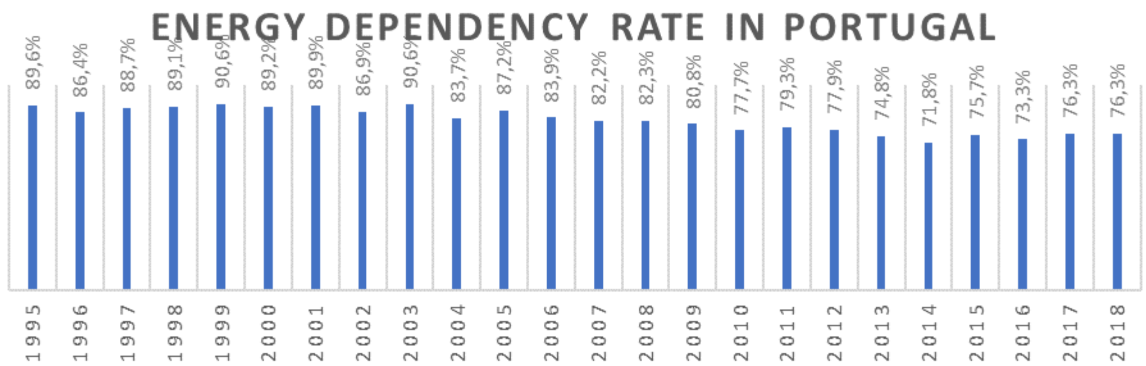


Figure 9 - Chart of the energy dependency rate evolution in Portugal from 1995 to 2018 (DGEG, 2019).

2.1.3. Portuguese regulation on energy performance

The last two decades have been a period of extensive development on the active legal instruments regarding building efficiency. This progress was propelled by the continuous endeavour of European institutions on the confrontation of the galloping climate crisis. A lot of targets were drawn, but the most ambitious is the new European Climate Law, that sets 2050 as the year in which climate neutrality will be achieved amongst every EU member. Then, EU nations have to proceed to build their own legislation, according to European guidelines, in the effort of reaching the set goals.

Portugal has come a long way since the first approved legislation on the matter of energy efficiency in buildings. The original piece came into force in 1990, as consequence of the Decree-law No. 40/90, which constitutes the Regulation of Thermal Behaviour of Buildings (RCCTE 1990), the first of its kind, on the grounds of a perceived need for energy efficiency improvement on the building stock and also the required response to aspirations of both greater thermal comfort indoors and minimum possibility for the development of pathologies on the construction elements. Hence, the structural ambition of this document would be conveniently supported by the uniformization of technical knowledge. The success of this regulation would be determined by its correct implementation in the licensing stage and the openness of possible energy audits and inspection acts upon the project in hand. The 1990's RCCTE had some shortcomings but also, some strongpoints. Although, undemanding in some technical aspects, the regulation introduced new concepts on energy performance of buildings, such as minimum requirements for the buildings' envelope thermal performance and shading systems to prevent overheating in the summer, and redefined the standard for thermal comfort in the Portuguese construction sector. Additionally, it was the first European regulation that contemplated specific requirements for the cooling season. Even though the regulation was expected to be periodically revised, these improvements came to fruition, in the expected period, due to legislative inertia and the relative inexpensiveness of fossil-fuel based energy coupled with the uncertain feasibility of existing cost-efficient solutions.

However, in the following decade, the increasing penetration of HVAC systems in the consumers market, since it offered a reliable alternative to more traditional systems, incited an extreme growth in global electric energy consumption and consequently greenhouse gases (GHG) emissions. This problematic, was something that the existing regulation, the RCCTE 1990, could not handle effectively.

In 1997, the Kyoto Protocol established a new set of limits to, currently, 192 countries in the hopes of achieving a reduction of greenhouse gases emissions by an average of 5% against 1990 levels. This protocol operationalizes the United Nations Framework Convention on Climate Changes, which essentially asks the involved industrialized countries and economies in transition to adopt policies and measures in accordance with the agreed targets and report results periodically (Kyoto Protocol, 1997).

The modern version of the Portuguese legislation regarding energy performance of buildings, is mainly composed of transpositions of European Directives such as the Energy Performance of Buildings Directive (EPBD, 2002/91/EC), which was recast in May 2010 (2010/31/EU) and reviewed in May 2018 (2018/844/EU). The original directive (2002/91/EC) laid down 5 structural requirements: the general framework for a methodology of calculation of the integrated energy performance of buildings; the application of minimum requirements on the energy performance of new buildings; the application of minimum requirements on the energy performance of large existing buildings that are subject to major renovation; energy certification of buildings and regular inspection of boilers and of air-conditioning systems in buildings (EPBD, 2002).

The effective period of the "RCCTE 1990" came to conclusion through the transposition of the "EPBD 2002" into Portuguese law across three different pieces: Decree-law No. 78/2006, which approved the Buildings' Energy and Indoor Air Quality Certification System (SCE); Decree-law No. 79/2006, which approved the Regulation of Energy System for Climatization in Buildings (RSECE) and Decree-law No. 80/2006 which approved the recast of the original RCCTE.

The revision of these three diplomas was further agglutinated into one single legislation, the Decree-law No. 118/2013, after the first reform of the EPBD in 2010. Thus, this legislation ensures not only the transposition of the latest directive in reference, but also a revision of national legislation, which is embodied in improvements in systematisation and field of application by approving and establishing, in a single diploma, the Energy Certification System for Buildings (SCE), the Regulation on Energy Performance of Residential Buildings (REH) and the Energy Performance Regulation of Trade and Service Buildings (RECS). The updating of existing national legislation involves changes at various levels, with emphasis in the clear separation of the scope of application of the REH and the RECS, which focuses exclusively on housing buildings and the latter on trade and services, simplifies technical conduct and administrative management of processes, while recognising the technical specificities of each type of building, in what is most relevant for the characterization and improvement of energy performance (Decree-Law No.118/2013).

The climate zoning system, reformed in one of the published ordinances of the active regulation, follows a new set of principles. Firstly, it is based in the Nomenclature of Territorial Units for Statistics (NUTS) of level III. Secondly, it defines three different climate zones for winter (I1, I2, I3) and summer (V1, V2, V3) seasons. The first are defined by the number of Degree-Days (DD)[5] corresponding to the heating season, with a reference temperature of 18ºC, and the last are defined by the mean exterior temperature related to the conventional cooling season ($\theta_{ext,v}$).

Table 1 - Principles for the determination of winter and summer climate zones in Portugal (Dispatch No. 15793-F/2013)

Principle	DD ≤ 1300	1300 < DD ≤ 1800	DD > 1800
Zone	**I1**	**I2**	**I3**
Principle	$\theta_{ext,v} \leq 20$ºC	20ºC < $\theta_{ext,v} \leq$ 22ºC	$\theta_{ext,v}$ > 22ºC
Zone	**V1**	**V2**	**V3**

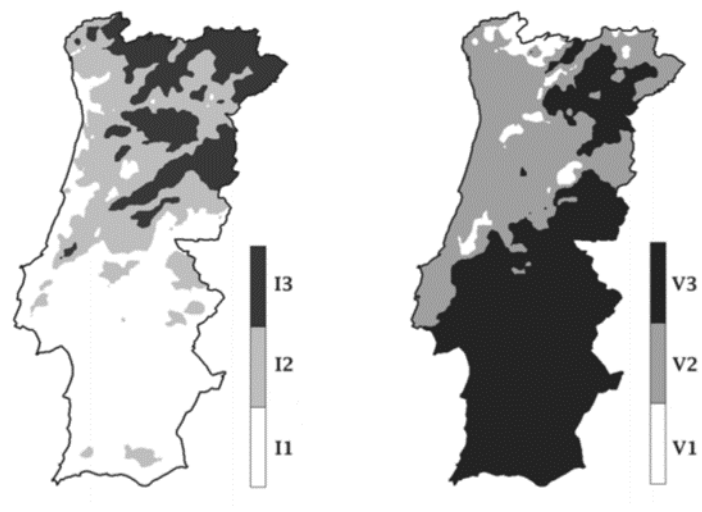


Figure 10 - Portuguese mainland winter and summer climate zones (Dispatch No. 15793-F/2013)

Table 2 depicts the evolution of the minimum requisites throughout the approved legislation. The RCCTE 1990 values are the same as in the 2006 version, for this reason the inclusion of this legislation in the table would be irrelevant. All the mentioned values relate exclusively to mainland Portugal, as the autonomous regions of Madeira and Azores have their own legislation. REH (2013) refers to the Ordinance 349-B/2013, which was active until December 2015, while REH (2016) refers to the Ordinance 319/2016, which is currently in force and sets new energy requirements that affect the maximum transmittance values (U_{MAX}) in the external envelope. Maximum and reference solar factor

[5] $DD = \Sigma(\mathrm{Ti} - \mathrm{Ta})/24$ [ºC/day], where Ti is the base temperature, 18ºC, and Ta is the mean exterior temperature during the heating period.

values (*g*) are appliable only with compliance of stablished requirements like percentage of glazed area in relation to pavement area.

Table 2 - Evolution of the main minimum requisites, since 2006 (adaptation from Barbosa (2020))

		RCCTE (2006)						REH (2013)						REH (2016)		
Thermal requisites		U_{MAX}			U_{REF}			U_{MAX}			U_{REF}			$U_{MAX} = U_{REF}$		
		I1	I2	I3	I1	I2	I3	I1	I2	I3	I1	I2	I3	I1	I2	I3
Ext. Env.	Vertical	1,80	1,60	1,45	0,70	0,60	0,50	1,75	1,60	1,45	0,50	0,40	0,35	0,50	0,40	0,35
	Horizontal	1,25	1,00	0,90	0,50	0,45	0,40	1,25	1,00	0,90	0,40	0,35	0,30	0,40	0,35	0,30
	Glazed	-	-	-	4,30	3,30	3,30	-	-	-	2,90	2,60	2,40	2,80	2,40	2,20

	RCCTE (2006)						REH (2013)					
	g_{Tmax}			g_{REF}			g_{Tmax}			g_{REF}		
	V1	V2	V3	V1	V2	V3	V1	V2	V3	V1	V2	V3
Low Inertia	0,15	0,15	0,10				0,15	0,10	0,10			
Medium Inertia	0,56	0,56	0,50	0,25	0,20	0,15	0,56	0,56	0,50		0,43	
Strong Inertia	0,56	0,56	0,50				0,56	0,56	0,50			
Ventilation	≥ 0,6						≥ 0,4					

The 2018 revision of the EPBD brought higher demands and new concepts to its previous version. Heavily influenced by the Paris Agreement of 2015, the EU strengthened its vision of developing an energy sustainable, competitive and decarbonized system as soon as possible, with a special attention on building stock, which represents nearly 36% of the total CO2 emissions in the union (EPBD 2018 point 6) For this purpose, EU members and other involved parties must establish clear policies and pursue investments that lead them to the expected goals in a short-term (2030), mid-term (2040) and long-term (2050) periods. This directive emphasizes the 2010's proposed measures and also focuses on the nearly zero-energy buildings (NZEB), either it being new construction (which are obliged to comply with NZEB requirements, following 2019 in public buildings and 2021 in the case of private buildings) or an existing building undergoing extensive refurbishments. Additionally, the directive sheds some light on the relevant part of building automation in achieving the NZEB category. Hence, the creation of an aptitude indicator for intelligent technologies (SRI) which is intended to be used for grading the feasibility of employing both information and communication technologies and electronic systems, in order to adapt buildings' operation to the necessities of its users and network, consequentially improving its energy efficiency and global performance.

In 2020, the Decree-Law No.101-D/2020 constituted the required transposition of the latest directive on energy performance in buildings to Portuguese legislation. In summary, this legal document establishes the appliable requirements in order to improve buildings' energy performance, and also constitutes the regulation for the updated Energy Certification System (SCE).

2.2. Portuguese Housing Stock Standards

To adequately serve the purpose of this thesis, it is important to understand the performance levels of the existing Portuguese housing stock, and its variation through most recent times. Having this in mind, this chapter will describe a general scope of this reality by means of statistical presentation and descriptive statements of five different approaches. These will be state of conservation of the building stock, rehabilitation, energy certification, and other complementary concepts and studies.

The current state of the building stock in Portugal is, in its majority, inadequate, mainly due to the scarcity of good design and construction standards up until very recent times. Vulgarly, the major focus of most Portuguese building developers has always been the achievement of cheap production instead of reaching a cost-efficient result that would, at least, match the user needs.

The concept of building efficiency is, in fact, a fresh idea in the Portuguese building sector and it was only strengthened since the European Union (EU) drafted the Energy Performance of Buildings Directive (Directive 2002/91/EC) which forced the renovation of Portuguese building regulations. This European directive enforces the development of strategies towards long term rehabilitation, confronting the expected energy crisis with more energy efficient housing and the increased preference for renewable energy sources in the hopes of reaching de decarbonization of the building stock, following Portugal's Roadmap for Carbon Neutrality 2050 (RCN 2050).

2.2.1. State of conservation of the building stock in Portugal and construction standards

The importance of building conservation and rehabilitation started to increase around mid-century XX in the European context. This rise in awareness of this aspect was substantially motivated by the large increase of the building stock in the sequence of World War II, which enforced the renovation of cities all around the European continent. For this reason, allied with the gradual revolution on building technologies, the development of national regulations and the integration of modern urban planning concepts, the idea of building longevity was launched.

The Portuguese regulation does not prominently predict the implementation of periodic conservation works on new and existing buildings nor it mentions any recommendation on this aspect. Which means that the Portuguese habits on maintenance of buildings are very scarce and are essentially considered only after the occurrence of anomalies.

Due to various decades of disproportionate development of new houses (**Figure 11**) (prior an active and reliable energy technical regulation) Portugal was confronted with a dramatic increase of family debt between the years of 1992 and 2002, from 18% to 100% (ADENE, 2011).

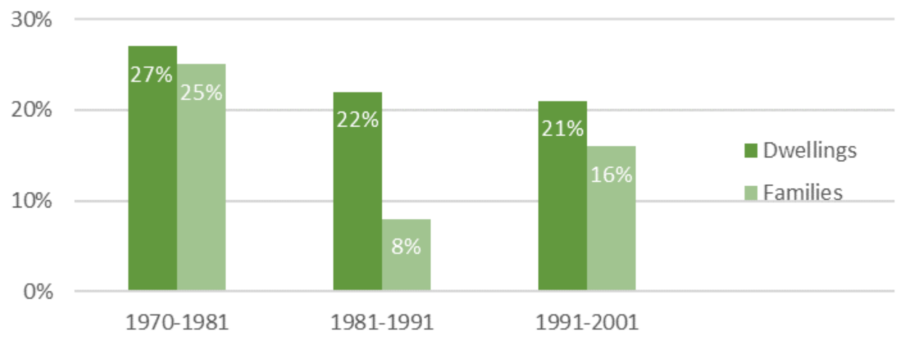


Figure 11 - Growth rate of dwellings and families in Portugal from 1970 to 2001 (INE Census 1970, 1981, 1991, 2001)

Hence, Portuguese families struggled to keep their houses in adequate conditions, even though, presumably, most did not possess suitable conditions to begin with. This created a great predicament as big urban cities like Porto and Lisbon presented a considerable number of buildings either degraded or in need of extensive repairs, forcing the construction sector to increase the focus on rehabilitation projects.

In relation to the construction standards, more specifically the standards on the integration of thermal insulation on the Portuguese building stock, it can be classified as moderately inadequate. as the first technical regulation of buildings' thermal behaviour was developed in 1990, which came into effect just after two decades of great investment in new construction that in most cases was not correctly regulated in this area. It should be mentioned that although this regulation was very important in setting the basic insulation levels for projects of new buildings and major refurbishments to ensure the satisfaction of thermal comfort indoors, there could be cases of licensed projects that would not be obliged to install wall insulation (Ferreira & Pinheiro, 2011).

As it can be observed in **Figure 12**, about 70% of the total number of classical buildings until the year 2011, which represents almost 2,5 million buildings, was constructed in periods prior the year 1990. This fact represents a significant prevalence of inadequate constructive solutions on today's buildings.

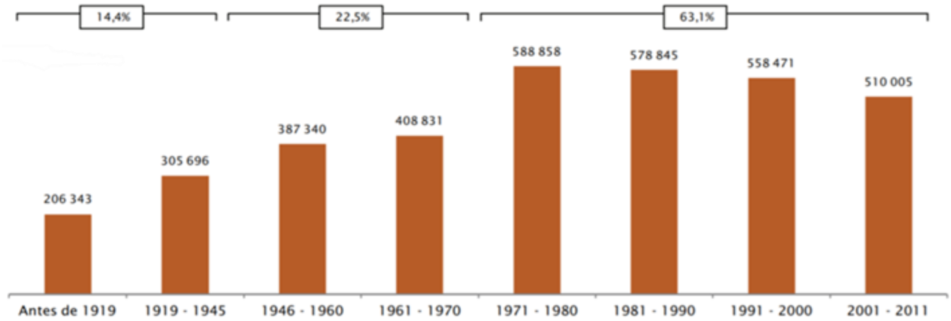


Figure 12 - Number of classical buildings per construction period (from INE, Census 2011)

The typical configuration of buildings' walls for each construction period is presented in the **Table 3**.

Table 3 - Typical configuration of walls on different construction periods, adaptation from ADENE (2011).

Before 1960	1960-1990	1990-2006	2006-2013	After 2013
				
Stone masonry	Simple or double wall of brick masonry	Double wall of brick masonry	Double wall of brick masonry	Double wall of brick masonry, or simple wall externally insulated
No thermal insulation	No thermal insulation	0 to 20 mm of thermal insulation	40 to 50 mm of thermal insulation	50 to 60 mm of thermal insulation

Table 3 appoints that 69% of buildings, up until 2011, had poor wall designs as they did not contemplate the integration of thermal insulation.

Additionally, the same study concluded that the typical roofing design only included a thermal insulation layer after 2006 and the predominant type of window designs in Portuguese buildings, up until 2011, were simple glass windows, with about 75% representation, which are, in great majority, worser solutions than double glass windows (INE, 2010).

2.2.2. Portuguese rehabilitation

In 2013, a study was conducted by the National Institute of Statistics (INE), with the objective of understanding the current state of rehabilitation of the Portuguese building stock, and it was observed that, between 2001 and 2011, the number of buildings in a deplorable condition had dropped by 36%, and a 40,4% drop in the stock of buildings in need of big repairs, as depicted in **Table 4**.

However, Portugal is still far away from the rest of Europe since, by 2014, the rehabilitation of the Portuguese building stock only represented 6,5% regarding the total activity of the construction sector, contrasting with the 37% average of other European countries (Decree-Law nº53/2014).

Table 4 - Rehabilitation of the Portuguese building stock between 2001 and 2011, from INE 2013

State of conservation	Typical buildings		
	2001	2011	Variation
	Number		%
With no need for restoration works	1 868 342	2 519 452	34,8
With need for restoration works	1 199 336	965 782	-19,5
Small restoration work	706 716	624 322	-11,7
Medium restoration work	329 605	244 303	-25,9
Extensive restoration work	163 015	97 157	-40,4
Very degraded	92 365	59 155	-36,0
Total	**3 160 043**	**3 544 389**	**12,2**

2.2.3. The SCE and energy certificates

Another one of the measures the Portuguese government projected to entice a better quality on the building standard was energy certification. The concept of energy certification was originally diffused along EU members through the 2002 EPBD, which incentivized the development of legislation on the delineation of diagnosis methods for the housing stock's energy consumption and polluting emissions, and also, to promote the progress on measures and strategies to act upon those identified problems. Even though there was no clear definition on a specific method of energy performance determination to be enforced, the common guidelines established in this version of the EPBD, in the case of housing stock, contemplate particular aspects like the characteristics of the envelope; natural and mechanic ventilation; heating and cooling systems; heating systems for sanitary hot water; building orientation and external climate influence on heat flux; and finally the contribution of renewable energies (Directive 2010/31/EU 2010). The flexible interpretation of these somewhat ambiguous guidelines resulted in a heterogeneity of transpositions to national regulation among the EU members (Majcen et al., 2013).

Therefore, the System of Energy Certification of Buildings (SCE) was approved by Decree-Law nº78/2006 and came into full force in 2009 when all new construction for housing and/or services or existing buildings or fractions of buildings, when concluding sales or lease contracts, were covered by the SCE. Owners must present potential buyers, renters, or tenants with an Energy Certificate (EC) issued by a Qualified Expert (QE) under the SCE. In the EC, one of the compulsory points, aims to present measures to improve energy performance and indoor air quality of buildings. The correction of constructive pathologies, the reduction of useful energy needs, by intervention in the envelope, and the use of renewable energies and energy-efficient systems are the expected outcomes (ADENE, 2011).

In 2013, the Decree-Law 118/2013, and all the proceeding dispatches and ordinances, updated the SCE to its latest version. The current SCE redaction establishes the distinction between two types of SCE certification, housing certification and business and services buildings certification. This version dictates the progress of the calculation methods, which is a steady-state method based on the European norm EN ISO 13790; the reduction of energy necessities; new energy efficiency reference values; and the clear promotion of rehabilitation and the integration of renewable energy. Also, the energy certification under the SCE is applicable to two different scopes of buildings or autonomous building fractions:

1. Licensing or previous communication of urban construction operations, which splits into two distinct stages:
   a. Design stage – application for a Pre-Energy-Certificate (PEC), which is one of the elements included in the licensing stage of the project.
   b. Construction works conclusion stage – where an EC is issued by a QE, approving that the execution stage of the project is compliant with regulation's requisites for new buildings and buildings subjected to extensive rehabilitation works.

2. Building stock, which in the specific case of housing applies to buildings undergoing any type of transactions.

The proposed calculation methodology to be followed by the QE, goes around the assessment of the subjected building through multiple parameters:

a) climate zone – a building's location dictates its energy performance due to the prevalent influence of weather conditions on useful energy necessities.
b) heat flux by transmission – in relation to the established heat exchanges, either superficial or linear, occurring in constructive elements of a building's envelope due to the thermal gradient in the element (1).

$$H_{tr} = \sum_i [U_i . A_i] + \sum_j [\psi_j . B_j] \quad [W/\circ C] \qquad \textbf{(1)}$$

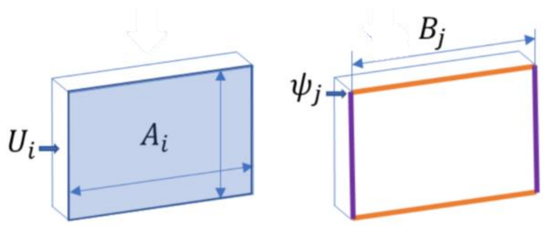


Figure 13 - Heat flux through transmission ("Guia SCE – Parâmetros de Cálculo" ADENE, 2020)

c) heat flux by ventilation – this concerns the heat exchanges due to the difference between inside temperature and the temperature fresh air flow (2). ($R_{ph,v}$ is renovations per hour; A_p is pavement area; h_c is the height of the ceiling)

$$H_{ve,v} = 0{,}34 \times R_{ph,v} \times A_p \times h_c \quad [W/\circ C] \qquad \textbf{(2)}$$

d) gains through the envelope – heat gains from solar radiation exposure of a building's surface (glazed and opaque areas).
e) internal gains – heat gains due to normal human activity inside a building (electronic equipment, artificial lighting etc.).

In practical terms, a submitted EC in the SCE domain confers a class to the assessed building, which indicates the energy efficiency of the building in relation to a reference performance. This means that the classification is based on a ratio between the global balance of energy exchanges of the building, while preserving the required conditions for thermal comfort indoors, and the global energy balance of the same building, subjected to the same conditions, but with a reference performance level (energy losses and gains through a reference envelop).

$$R_{NT} = \frac{N_{tc}}{N_t} \qquad \textbf{(3)}$$

Where: N_{tc} is the primary energy annual needs index; and N_t is the regulation limit value for the primary energy annual needs.

Table 5 - Energy Class for housing buildings

Energy Class	R_{NT} value
A+	$R_{NT} \leq 0,25$
A	$0,25 < R_{NT} \leq 0,50$
B	$0,50 < R_{NT} \leq 0,75$
B-	$0,75 < R_{NT} \leq 1,00$
C	$1,00 < R_{NT} \leq 1,50$
D	$1,50 < R_{NT} \leq 2,00$
E	$2,00 < R_{NT} \leq 2,50$
F	$R_{NT} > 2,50$

Note: The minimum energy class for new buildings under the SCE is B-, while in the case of extensive rehabilitation works, the minimum energy class is C.

At this time, in 2021, ADENE (the Portuguese Energy Agency), which is the entity responsible for the SCE, managed to achieve a database of about 1,4 million buildings with EC under the SCE. Housing buildings represent about 88% of the total submitted EC under the SCE, and almost 81% of these refer to existing housing buildings (SCE, 2021).

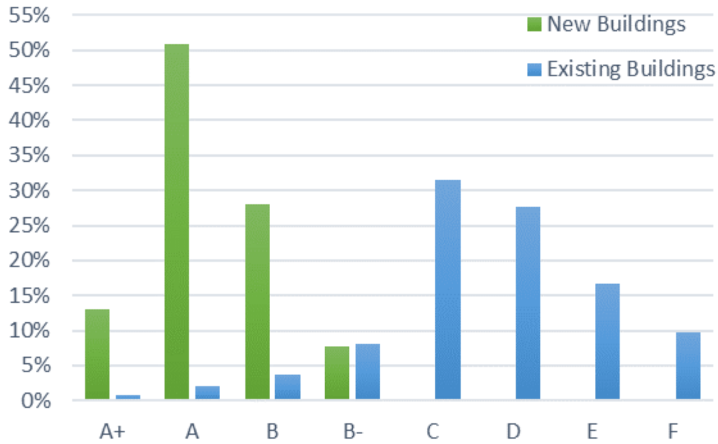


Figure 14 - Distribution of EC by energy class – new buildings and existing buildings (SCE, 2021).

Figure 14, it is observable that about 85% of EC relative to existing buildings have a C or even lower energy class. This means that the average performance of existing building stock is at least 50% worse than the reference performance. On the other hand, a high amount of EC relative to new buildings tend to present higher levels of performance than the minimum requirements.

2.2.4. Complementary concepts and studies

In 2014, the BPIE (Building Performance Institute Europe) conducted an in-depth study and concluded that Portugal is in second place in the EU in the Excess winter deaths index (EWDI). The same study reveals that in the year 2012, 43% of the Portuguese population did not have the financial capacity to have the minimum conditions of thermal comfort (BPIE, 2014).

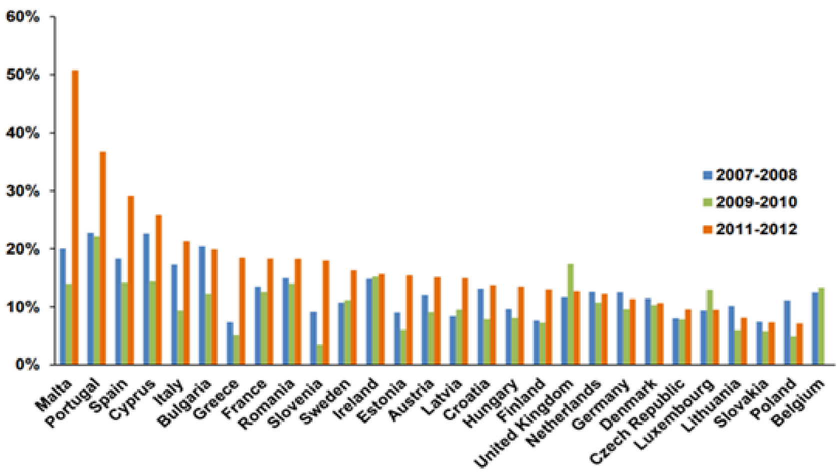


Figure 15 - Excess winter deaths index (EWDI) between 2007 and 2012 in the EU28 (BPIE calculation based on Eurostat data)

2.3. Autonomous housing, the Passive House and nZEB models

Thermal self-sufficient houses, or autonomous houses, relate to buildings with optimal functionality designs that intelligently manipulate their resources and restraints, in order to achieve the best energy performance, allied with the integration of systems that, through autonomous sources, complement the remaining energy needs, providing high quality of life to its occupants. Currently, there are two main models of self-sufficiency in buildings, the Passive House and NZEB approaches.

Although being originally created for colder climates, the Passive House (PH) norm, reveals a lot of promise on its application on Mediterranean climates. The Passive House model, or, as originally named, Passivhaus, was developed in 1991 in Darmstadt-Kranichstein, Germany as a result of a research project that aimed to obtain a more optimal system to deliver the required thermal comfort indoors, since the then current German building code revealed too much compliance with excessive energy consumption to ensure heating needs. "*Passive Houses are buildings which minimize heat flows across the building envelope and thus combine high thermal comfort, extremely low energy demand and, due to simplified mechanical services systems, relatively low lifecycle cost.*"(Schnieders et al., 2015).

The Passivhaus norm is recognized as the most exceptional model in energy efficiency, as its worldwide application demonstrates a cut of 80 to 90% less heating energy needs than conventional new buildings, for only 5 to 10% additional building cost (Schnieders et al., 2015). Due to its somewhat burdening restrictions and demands, the model achieves the highest standard of cost-efficiency. Also, the proved versatility of the PH norm, as it has been applied successfully in a diversity of climates, without the need for great restrictions to architectural design, is a very compelling argument.

This concept is based in 5 different practical points: good insulation of the building's envelope, high quality windows, airtightness, ventilation heat recovery system, and the avoidance of thermal bridges. Although, these are the main focus points to achieve certification of PH norm, adequate architectural design and attention to the variable specificities of each climate (i.e. air humidity, solar radiation levels, average temperature variation etc.) are very important parameters to ensure the best performance in PH buildings, and the prevention of problems like overheating, which is the main endangerment associated with the Mediterranean climate.

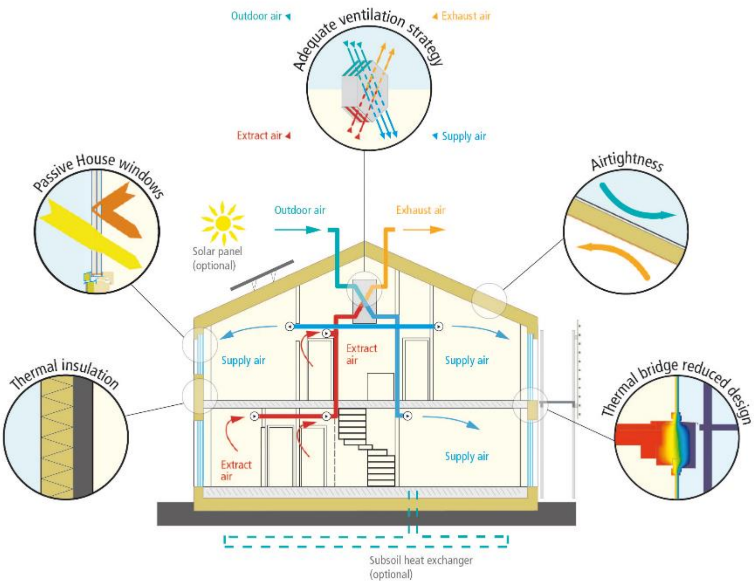


Figure 16 - Application of the 5 Passive house principles, from passivehouse.com

The *Passive House Institute*, the superlative organization in this subject, recognizes the "*Associação Passivhaus Portugal"* as the institution in charge of the PH model development in Portugal.

Table 6 - Energy performance requisites for the PH norm in the Portuguese climate from www.passivhaus.pt

Energy performance requisites for the PH norm in the Portuguese climate	
Annual heating necessities Or heating load	< 15 kWh/(m^2.year) < 10 W/m^2
Annual cooling necessities Or cooling load	< 15 kWh/(m^2.year) + dehumidification contribution < 10 W/m^2
Primary Energy	PE < 120 kWh (m^2.year) or PER < 60 kWh (m^2.year)
Air tightness	Blower door test (n_{50}) < 0,6 rph
Thermal comfort	Temperature between 20 and 25 ºC, and excessive temperature under 10% of time

The "Rua do Mar - House A" integrates a development plan of two single family houses. The site is located near the limits of the urban area of Ílhavo, a town located in the Aveiro district in the north coast of Portugal. This building, concluded in 2012, is one of the few buildings with the official certification from the Passivhaus Institute on the authentication of PH norms. The following table describes the solutions that the architects Óscar Graça (COG) and João Gavião (Homegrid) projected for the thermal envelope and the mechanical systems adopted in this construction. In sequence, it is also presented the confirmation parameters that evaluate the compliance with PH norms. These values are determined according to the Passive House Planning Package (PHPP), which is a design tool that aids designers and architects on the development of PH projects.

In the end, the global construction cost was about 1200 € for square meter of treated floor area, which is approximately 50% higher than typical construction costs, contrarily to the previously mentioned statement. However, this optimum system serves a greater purpose in the savings potential of the building throughout its life cycle.

Table 7 - Description of the project "Rua do Mar - House A" and PH norm compliance, from the passivehouse-database.org

Thermal Envelope:

Exterior wall	Basement floor / floor slab	Roof
Plaster 10mm EPS [0,037 W/(m.K)], 100mm Thermal Block [0,27 W/(m.K)], 250mm Plaster, 20mm U-value = 0.262 W/(m².K)	laminate floor,8 mm screed, 50mm lightweight concrete [0,46 W/(m.K)], 120mm fungiform slab [0,85 W/(m.K)], 250mm XPS [0,035 W/(m.K)], 50mm U-value = 0.421 W/(m².K)	Ceramic tile over wood structure Breathable barrier membrane XPS [0,035 W/(m.K)] + timber rafter (5%), 150mm Fungiform slab of clay blocks [0,85 W/(m.K)], 250mm Plaster, 20mm U-value = 0.234 W/(m².K)
Entrance door	**Frame**	**Glazing**
Anicolor Ati series Double aluminium panel with 25mm of polyurethane U-value = 0.97 W/(m².K)	Anicolor, ATi Aluminium frame with thermal rupture, [standard Uf-value 2,7 (W/m.K)], small frame dimensions U-value = 1.64 W/(m².K)	Double glazing (Planilux 6mm + Argon 16mm WE + Stadip Planitherm Ultra N 44.1mm) and Chromatech Plus spacers U-value = 1 W/(m².K) g-value = 60 %

Mechanical Systems:

Ventilation	Heating installation	Domestic hot water
Nilan, Compact P ventilation for supply and extract air with heat recovery Specific heat recovery efficiency 76%.	Exhaust air heat pump system (Nilan, Compact P) Radiators on bathroom and bedrooms on the first floor supplied by wood burning stove with water exchanger Romotop KV 6.6.2 and by a small gas boiler	Exhaust air heat pump system (Nilan, Compact P); thermal solar system: 2 Sonnenkraft solar panels 500N and 300L deposit Wood burning stove with water exchanger Romotop KV 6.6.2

PHPP values:

Air tightness	Annual heating demand	Heating load	Non-renewable Primary Energy
n_{50} = 0.54/h pressure test value	11kWh /(m².year)	11 W/m²	74kWh/(m².year) on heating installation, domestic hot water, household electricity and auxiliary electricity

Figure 17 - Outside view of the "Rua do Mar – House A" building, from www.lidera.info

Despite being around for a shorter time relative to the PH model, the nearly zero-energy building (NZEB) concept has been very impactful, especially in building legislation. In 2010, the recast of EPBD introduced this new concept of NZEB, defined has being buildings with very high energy performance, and having very small or nearly null energy needs, which are covered in great scale by renewable energy sources, produced either locally or in the proximity. The EU members were then expected to endorse this model and also ensure that the transition of new public buildings to NZEB was achieved by 2018 and the same applies to every other new building until 2020. The approach on the NZEB model should sit on these 3 focal points: passive energy-saving technologies, energy-efficient building service systems, and renewable energy production technologies (Cao et al., 2016).

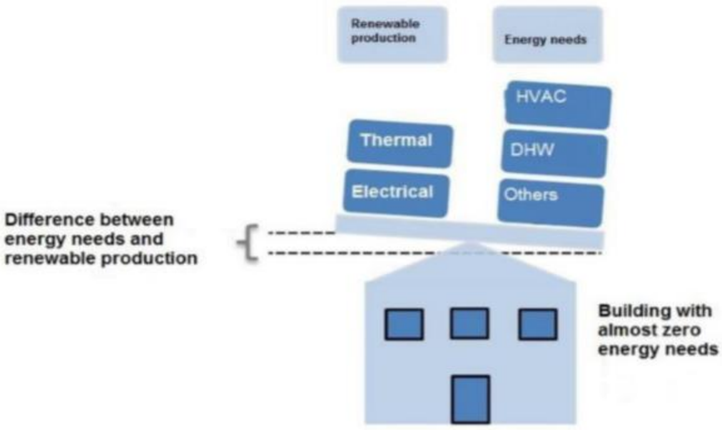


Figure 18 - Interpretation of the NZEB concept by DGEG, 2013

The transposition of this matter to Portuguese law, as previously explained, was delivered by the Decree-Law No. 118/2013, even though, further clarifications and quantifications only came to fruition in more recent legal pieces, the Ordinance No. 42/2019, and Ordinance No. 98/2019. While both identify the quantitative requisites and numerical limits for the definition of a NZEB's performance, the first one addresses the NZEB requirements in buildings destined to business and services (RECS), and the latter to buildings destined for housing (REH).

Therefore, alongside with other appliable regulation requisites, the houses that approach the NZEB model must cumulatively comply with the following points displayed in **Table 8**:

Table 8 - Requirements for nZEB houses from Ordinance 98/2019

Requirements for nZEB houses	
Useful heating energy: N_{IC} and N_{I} = calculated and nominal useful energy index, respectively	N_{IC} / $N_{I} \leq 75\%$
Primary energy: N_{TC} and N_{T} = calculated and nominal primary energy index, respectively	N_{TC} / $N_{T} \leq 50\%$
Renewable energy sources must cover the climatization and SHW needs	$\geq 50\%$

2.4. Active and Passive solutions on market

This subchapter's subject is the development of the previous subchapter, as passive and active systems are, essentially, the resources by which the mentioned models achieve their intended goals. Although, it can be very complex to settle which one is the best path towards energy efficiency in buildings, there is a clear distinction between active and passive solutions regarding their application in PH and NZEB models, as the latter one always assumes the leading role in PH whereas, the NZEB model can import diverse relevance conjugations of the two systems. This also contributes to the idea that PH always comply with NZEB standards whilst, NZEB do not necessarily comply with the PH norm (Passivhaus, 2021).

Passive solutions are systems that once applied to a building's design, confer certain properties that increase its energy efficiency in order to consistently deliver appropriate conditions for the thermal comfort of its occupants, either through the reduction of heat loss in the heating season, and heat gains in the cooling season, or by the employment of techniques or devices that promote an intelligent dynamic between external resources and the building's interior.

Active solutions are systems that, as predicted in the NZEB model, counterweight the inherent energy consumptions of the building and the natural activity of its occupants, with the local generation and storage of energy positively influencing the global energy balance of the building.

Taking these two different categories into consideration, a review of solutions on market was conducted. For the passive solutions, these will be subcategorized into several types of systems: external walls, roofing, which concern to the opaque envelope; glazed area solutions; solar protection solutions; and natural ventilation solutions. Lastly, the active solutions will be heavily represented by renewable energy systems as they represent a great option for off-grid houses and for the intended purpose of this paper. These will be subcategorized in solar technologies and biomass heating systems.

2.4.1. Passive solutions – external wall systems

2.4.1.1. ETICS

ETICS, or *External Thermal Insulation Composite System*, is a popular system of insulation mainly because of its comprehensive range of solutions, which can perform to different levels of demands, the versatility of application, and reliability as system holders must guarantee a certain level of quality of performance and be subjected to the European Organization for Technical Assessment (EOTA)[6] protocols. This particular system is based on the increment of thermal inertia of buildings by mitigating the heat transfers between the outside and external walls, exemplified in **Figure 19**. It is also considered to be a great system for the elimination of thermal bridges along the envelope, alleviating the probability of health endangerment due to hygrothermal issues in the indoor surfaces, relative to either no-insulation

[6] Organization set up by the Regulation (EU) No 305/2011, regarding the standardization of construction products, and is responsible for the development and publication European Assessment Documents (EAD) and the establishment of procedures and guidelines for requested European Technical Approvals (ETA). In this way, EOTA contributes for the diffusion of best practices, in order to promote greater efficiency and service to the construction sector, throughout the EU members.

or other thermal insulation technics. Therefore, when correctly applied, it can improve the energy balance of new and existing buildings in the long term.

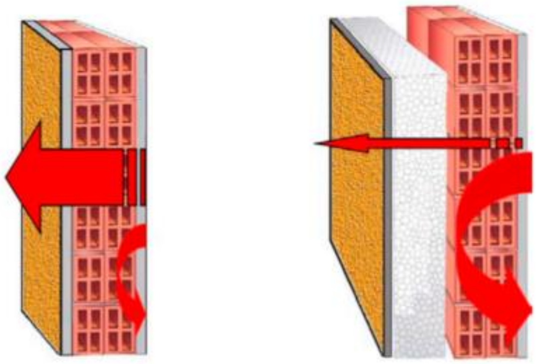


Figure 19 - Exemplification of ETICS advantages regarding thermal inertia of walls (APFAC ETICS Manual 2018)

There are two types of ETICS, bonded or mechanically fixed. The typical system components are, in application order (**Figure 20**): adhesive, thermal insulation material, anchors (if required), base coat, reinforcement mesh (usually fibre glass), and finishing layer (finishing coat with key coat and decorative coat). Some popular choices regarding the thermal insulation material are shown in **Table 9**.

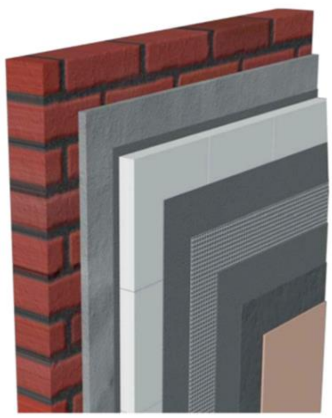


Figure 20 - Typical constitution of ETICS (APFAC ETICS Manual 2018)

Table 9 - Some principal characteristics of insulation materials (Adaptation from "APFAC ETICS Manual", 2018)

Material	**Thermal Performance λ (W/mK)**	**Indicative Density (kg/m^3)**	**Reaction to Fire**	**CE Marking/ Product Certification**
Expanded Polystyrene (EPS)	0,035 – 0,038	17 – 22	Class E	EN 13163
Extruded Polystyrene (XPS)	0,033 – 0,037	30 – 33	Class E	EN 13164
Mineral Wool (MW)	0,034 – 0,038	70 – 150	Class A1/A2	EN 13162
Expanded Cork (ICB)	0,037 – 0,040	110 – 120	Class E	EN 13170

As previously mentioned, European Technical Approval Guidelines (ETAG) establish the parameters, which technical approvals should be conducted by, in order to ensure proper certification for a product or system with intended use in construction and the European Economic Area (EEA). In this effort, ETAG 004-2013, the active version of the guideline for technical approval of "ETICS with Rendering", sets the performance requirements, the verification methods used in these examinations of performance as well as the assessment criteria and the presumed conditions relative to the design, execution and use of these systems. Furthermore, this document defines the essential requirements regarding seven aspects: mechanical resistance and stability; safety in case of fire; hygiene, health and environment, safety in use; protection against noise; aspects of durability and serviceability, and energy economy and heat retention. (ETAG 004, 2013) The last aspect serves the purpose of this paper, and for that reason will be the main focus from here on.

The increment of thermal resistance associated with the installation of ETICS on substrates is provided by the characteristic thermal resistance of the insulation products ($R_{insulation}$), which should be determined in compliance with respective norms (i.e. in the case of EPS, the calculation should comply with EN 13163), allied with the value for the render layers, as shown in equation (4), which can be determined either by the tabulated R_{render} (R_{render} equals approximately 0,02 m^2K/W), or through testing in compliance with EN 12667 or EN 12664.

$$R_{ETICS} = R_{insulation} + R_{render} \left[\frac{m^2.K}{W}\right] \quad (4)$$

Additionally, when talking about the thermal performance of systems like ETICS, it should be brought to consideration the thermal bridges linked with eventual mechanical fixings, as they potentially constitute a relevant mean of heat transfer through the insulation layer. This correction is calculated via the equation (5):

$$U_c = U + \Delta U \left[\frac{W}{m^2.K}\right] \quad (5)$$

$$U = 1/(R_{ETICS} + R_{substrate} + R_{se} + R_{si}) \quad (6)$$

$$\Delta U = (\chi_p * n) + (\Sigma\psi_i * l_i) \quad (7)$$

Where: U_c stands for the corrected thermal transmittance of the global solution, wall plus ETICS, including the influence of thermal bridges; U is the same as the previous but without the consideration of thermal bridges (6); $R_{substrate}$ is the thermal resistance of the substrate wall, and both R_{se} and R_{si} are the respective thermal resistance of the external surface and the internal surface; ΔU stands for the correction term of the thermal transmittance of the mechanical fixing devices (7); χ_p is the point thermal transmittance value of the anchor [W/K], which assumes different values in relation to the type of material; n stands for the number of anchors per m^2; ψ_i is the linear thermal transmittance value of the used profile [W/(m.K)]; l_i is the length of the profiles per m^2 (ETAG 004, 2013).

Also, installation manuals and standard procedures have been promoted and developed by dedicated organizations like the *European Association for External Thermal Insulation Composite Systems* (EAE), and, in the Portuguese context, the *Associação Portuguesa dos Fabricantes de Argamassas e ETICS* or APFAC, contributing to further clarifications on coexisting national building codes and European guidelines, and the diffusion of good practices on the handling of these systems.

2.4.1.2. Internal insulation

Parallel to ETICS, internal insulation is also a popular insulation system, even though it is based on a conflicting principle. In this system, the thermal inertia of the envelope is significantly reduced by the installation of insulation layer on the internal side of external walls. This contributes to a list of disadvantages in relation to ETICS: persistency of thermal bridges resulting in greater heat losses and potential hygrothermal issues; arguable inefficiency concerning energy performance of the envelope due to the non-exploitation of thermal properties of walls; unprotection of structural elements relative to possible degradation caused by external conditions like extreme weather, dampness and frosting and defrosting cycles; reduction of usable implanted area. However, it should be taken into to consideration when dealing with some cases of retrofitting buildings as this technique will not disturb the protected architectural design of the façade.

However, in the economic standpoint, this system has revealed to be more advantageous relative to ETICS. This was one of the conclusions of the study developed by (Kolaitis et al., 2013), focusing on the comparative assessment of internal and external insulation systems in the retrofitting of a standard one-storey apartment in Greece, through a series of parametric studies and analysis of detailed numerical simulations. The authors concluded that, although both systems significantly contribute to the reduction (by 21-89%) of HVAC energy consumptions and the potential for hygrothermal issues are very reduced in the typical warm Mediterranean climate regions (Csa in the Koppen classification), the internal insulation system requires 50% less investment cost than the other system, and consequently registers a lower payback period.

There are two possible configurations for typical internal insulation techniques, schematized in, differing in the thickness of the interior cladding.

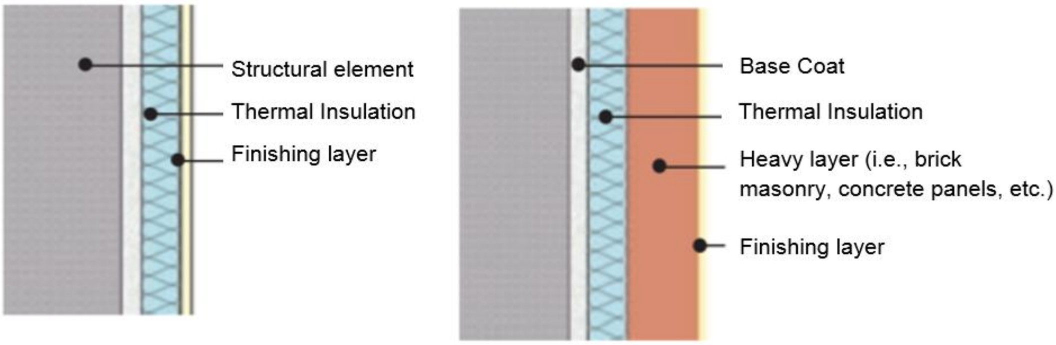


Figure 21 - Typical configurations of internal insulation technique (Adaptation from ADENE (2011)).

The configuration with heavier interior cladding mitigates, although not considerable, the previously appointed inefficiency due to the installation of a heavy layer, for example brick masonry, which provides an increment to the thermal inertia of the envelope, consequently increasing the potential for passive gains of heat indoors.

Analogous to ETICS, the global thermal transmittance of the solution depends on the thickness and material of the insulation layer. Nevertheless, it should be mentioned that the relation between thermal conductivity (λ) and optimum thickness (χ_{opt}) of the insulation material is non-linear, as validated in the study Mahlia et al. (2007), and it is characterized by the polynomial function of $\chi_{opt} = a + bk + ck^2$, where a = 0.0818, b = 2.973, and c = 64.6 regarding the installation of fibreglass-urethane as an insulation material. This means that the increase in the investment in insulation will translate into greater thermal resistance and consequently reducing the cooling load, which in the case of the Malaysian tropical climate (studied region) is the imperative condition. However, after a certain point of insulation thickness, the cost effectiveness of the solution will start to decrease, as the potential savings of the installation will not surpass the needed investment cost.

2.4.1.3. Ventilated façades

Similar to ETICS, ventilated façades are based in the principle of installing an insulation layer on the external surface of a building's opaque envelope, significantly reducing heat losses through thermal bridges, and taking profit from the characteristic thermal inertia of these elements. Nevertheless, these systems offer other positive aspects, as the introduction of a layer of air between the insulation material and the external layer promotes a reduction of internal condensations. Once again, to ensure good practises in the design and installation of this system, the EOTA developed the EAD 090062-00-0404 entitled "Kits for external wall claddings mechanically fixed". This document establishes the acceptable requirements for the components to be assembled in construction sites and dictates the points of expected compliance on behalf of manufacturers. The typical composition of a ventilated façade is as shown in **Figure 22**.

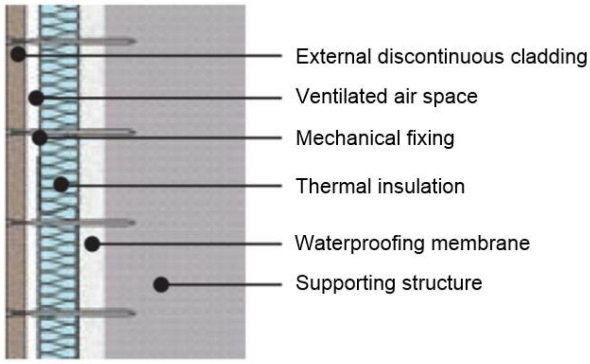


Figure 22 - Typical constitution of a ventilated façade (Adaptation from ADENE (2011)

This EAD's definition of claddings is a non-load-bearing element of construction that contributes to the protection of the structural elements into which they are mechanically fixed. The external cladding must be sectioned for fire safety and wind pressure purposes. However, this system can only be classified as ventilated if the distance between the cladding elements and the insulation layer is 20 mm, and as long as the eventual local reductions of air space (between 5 and 10 mm) do not compromise the draining and ventilation function. Additionally, the ventilation openings must, at least, be envisioned at the building base point and at the roof edge, as well as assuring a minimum of 50 cm^2 per linear meter for the cross-section.

In relation to the system's thermal performance, the extensive range of configurations between different types of cladding and thicknesses and thermal resistances of the insulation layer concedes a great array of solutions to various needs. The authors (Ciampi et al., 2003) and (Balocco, 2002) studied the energy performance of this system and achieved similar conclusions: energy savings increase with the rise of the ventilated air space width, to the limit of 15 cm. Natural ventilation in the cavity outputs a very positive performance all year long: about 60% of reduction of daily heat losses relative to non-ventilated façade in the heating season and 40% reduction of cooling necessities in the summer. However, the high investment cost associated with this system and restrictions on the modification of the architectural design of façades can be two very deterring arguments.

2.4.1.4. Double wall façades

Double wall façades are characterized by various solutions outlined by two main constituents: the designed structural elements and the computed thermal insulation solution, exemplified in **Figure 23**. The first one is described by two layers (with variable thickness) of either masonry wall or by a combination of concrete wall and masonry wall. The second part can be defined by three different solutions: no thermal insulation; insulation material completely filling the gap between both layers, and insulation material partially filling the gap between both layers. In the second and third cases, some of the commonly used insulation materials are: EPS, XPS, MW, ICB and polyurethane (PUR). Also, it should be mentioned that in the third case, the insulation should be mechanically fixed to the inner layer and the correspondent air gap should not be under 30 mm (preferably 50 mm) so that it can be considered as a non-ventilated air space (LNEC, 2006).

Double layer walls are a very traditional constructive solution in Portugal which means that it is does not require skilled labour nor special materials. Also, the inner layer of masonry concedes a good potential for positive contribution to inside temperature. Still, the elimination of thermal bridges along the interception of other construction elements like beams, columns and shutter boxes is necessary in order to achieve the best global performance.

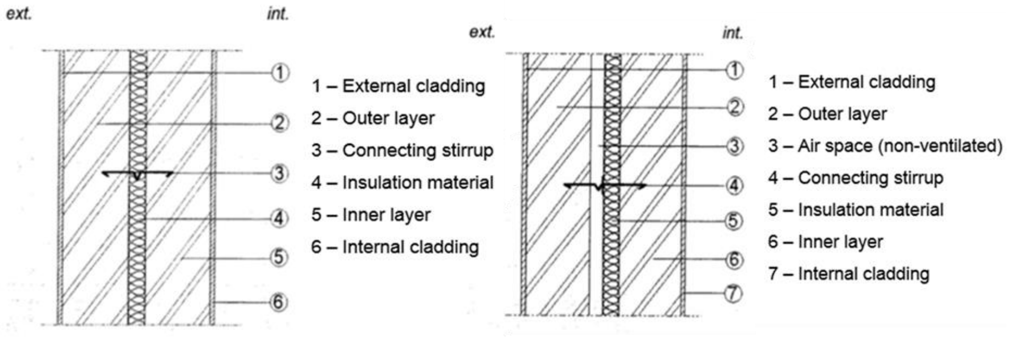


Figure 23 - Exemplification of two different configurations of insulated double wall façade (Adaptation from LNEC, ITE 50)

2.4.1.5. Passive solar walls

The idea behind these wall systems is the maximization of passive solar gains. Typically composed by a concrete wall and an outer covering of a glazed material, these uniquely designed walls absorb and conserve solar energy and then radiate heat indoors. Originally created by E.S. Morse in the 19th century, passive solar walls have seen various inspired designs like the one developed by Trombe et al, named Trombe wall. The thermal performance of this system can assure savings of about 32,1% on heating energy, when considering an optimal point in the relation between thermal performance and investment cost, in a Life Cycle Cost analysis (Jaber & Ajib, 2011).

Although the main preference for the adoption of these systems is in colder climates, insulated Trombe walls and composite solar walls can be very relevant choices for hotter climate region (Sadineni et al., 2011).

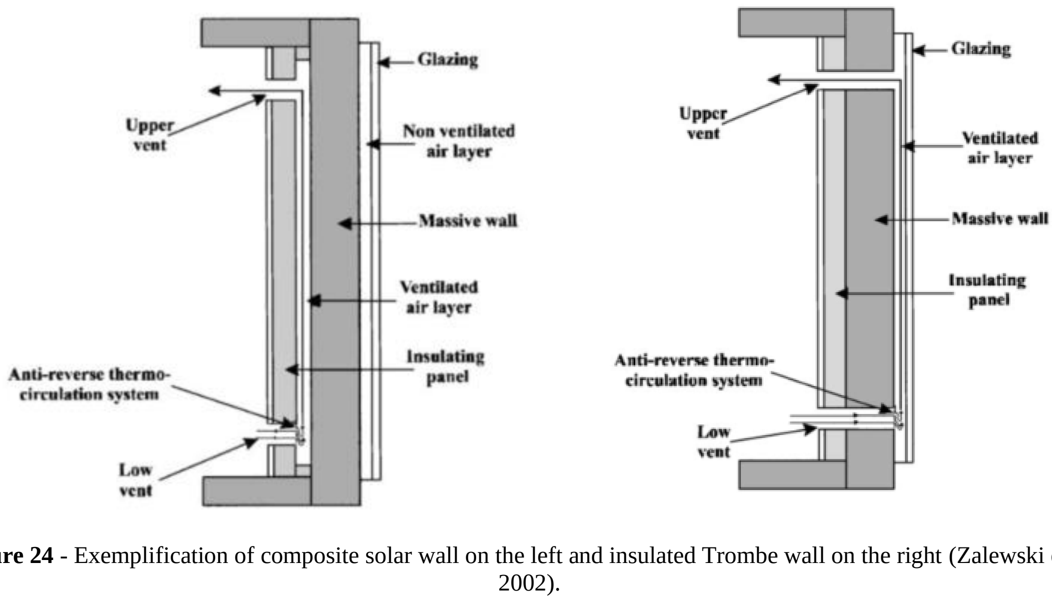


Figure 24 - Exemplification of composite solar wall on the left and insulated Trombe wall on the right (Zalewski et al., 2002).

2.4.2. Passive solutions – Roof systems

2.4.2.1. Pitched roof, insulation at rafter level

This solution consists in the installation of thermal insulation materials between and/or laid over the structural system (rafter) of a pitched roof, and for that reason it can provide comfortable conditions for occupants. However, these light structures, often made from wood or metal elements, are not very keen in providing passive climatization of the indoor space as their contribution for thermal inertia is very weak. Also, this installation requires thoughtful consideration of involving conditions and special attention to air tightness and vapor diffusion design.

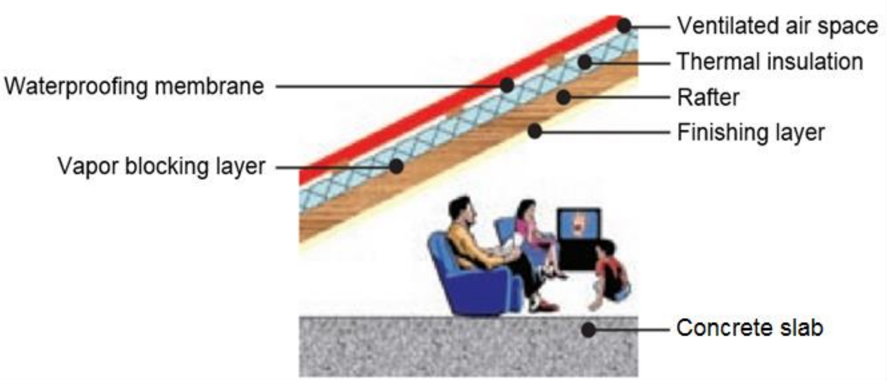


Figure 25 - Exemplification of the composition of a pitched roof with insulation at rafter level (from ADENE (2011)

2.4.2.2. Pitched roof, insulation at ceiling level

This solution optimizes the thermal inertia contribution of the ceiling as it is based on the installation of thermal insulation on top of the ceiling slab or ceiling joist. Hence, the lofted area, even though unhabitable in order to prevent damages to the insulation material, serves a great purpose as the ventilation of this space confers strong benefits to global thermal performance and reduces risks of hygrothermal issues on this section of the building. Additionally, it is a relatively cheap solution as the installation of the insulation material is very simple and low demanding, meaning that this solution can be installed with a great variety of thermal insulation systems as they are not subjected to harsh conditions.

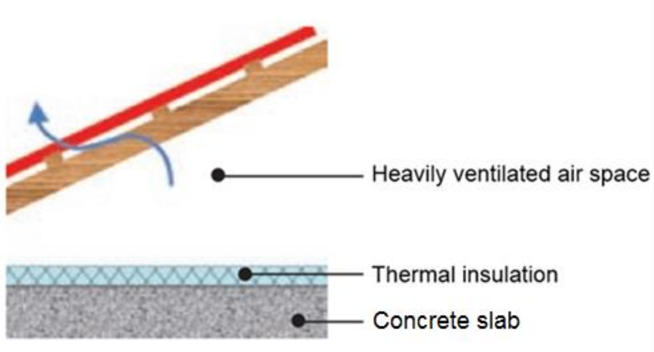


Figure 26 - Exemplification of the composition of a pitched roof with insulation at ceiling level (from ADENE (2011))

2.4.2.3. Ventilated and micro-ventilated roofs

As previously observed, the integration of ventilated walls on a building's envelope promotes the reduction of thermal loads and consequently increases energy savings throughout the year. For this reason, the implementation of this concept on roofs should also be considered as a viable option on improving in low-energy-consumption buildings. This solution consists in the installation of an air gap between the external cladding and the insulation layer, above the bearing structure of the pitched roof. The air flow in this duct has a considerable impact on reducing the heat transfer through the roof structure into the building. In a study conducted on ventilated and micro-ventilated roofs' energy performance, Ciampi et al. (2005), concluded that these solutions could effectively improve energy savings by 30% in relation to non-ventilated roofs and that these potential savings should increase as the width of the air gap increases, to an upper limit of 15 cm. However, the length of the pitch negatively affects the growth of the savings, and for that reason, it is convenient to divide the system into to several sections along the pitch. Additionally, in order to reduce heat losses in the heating season, the ventilation on the air gap should be minimal, and just enough to ensure the dissipation of eventual condensation.

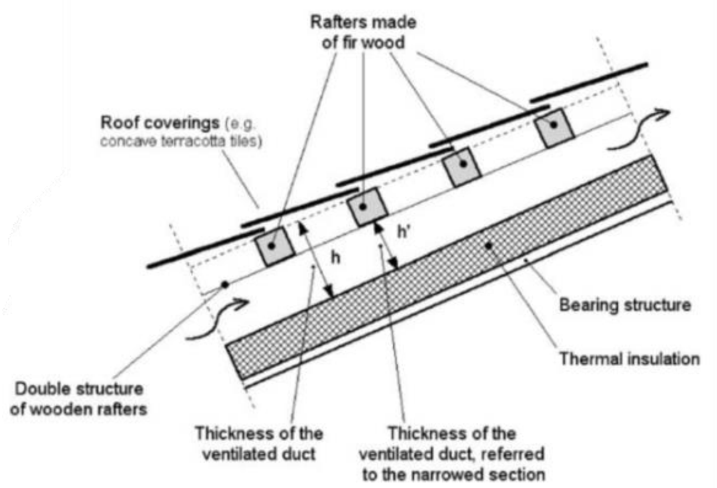


Figure 27 - Typical section of ventilated roof system (from Ciampi et al. (2005)

2.4.2.4. Inverted flat roof

The typical constitution of an inverted roof is shown in **Figure 28**. This system's name is due to the installation of the thermal insulation above the waterproofing layer. In order to ensure proper performance, the system must be established with a minimum slope of about 2% and the layer of thermal insulation should be continuous. The respective European guideline for technical approval, the ETAG 031, sets the requirements for "Inverted Roof Insulation Kits". These kits are defined as consisting of thermal insulation and at least on more component between filter layer, separation layer or a water flow-reducing layer. Regarding the specific thermal performance of these kits, it is considerably influenced by the contribution of the thermal insulation material which must be determined in accordance with the respective product standards and take in consideration the correction of the thermal resistance (R_{cor}) due to expected moisture levels, as shown in equations (8) and (9).

$$R_{cor} = R_D / F_m \qquad (8)$$

Where: R_D is the declared thermal resistance and F_m is the moisture conversion factor.

$$F_m = e^{f_\psi * \psi_{cor}} \qquad (9)$$

Where: f_ψ is the moisture conversion coefficient [m^3/m^3], according to EN ISO 10456; and ψ_{cor} is the calculation value for moisture content [m^3/m^3], which calculation is clarified in the ETAG 031.

This guideline addresses two thermal insulation materials, EPS and XPS, as these deliver the most adequate performances in these conditions. The placement of the thermal insulation layer above the waterproofing layer confers a greater durability to the system, due to the fact of it being more protected from harmful climate conditions. On the other hand, the over time performance of the thermal insulation is significantly reduced due to its exposure to moisture, and for that reason the attention to upper protection requirements is very high, consequently increasing the exploration costs.

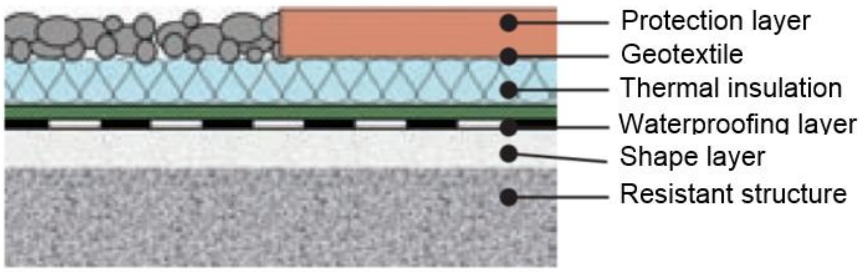


Figure 28 – Exemplification of an inverted flat roof (from ADENE (2011)).

2.4.2.5. Green roof

Green roofs are layered composite roofing systems essentially comprised by a waterproofing membrane and above all a growing medium as well as the vegetation layer itself. The adoption of this system in buildings has been studied since the beginning of the century, and it is revealing to be an interesting passive cooling technique. Additionally, some of the studied benefits associated with the incorporation of green roofs are stormwater management (Mentens et al., 2006) extension of roof life (Teemusk & Mander, 2009), improved air quality in urban scenarios and reduction of urban heat island effect (Banting et al., 2005).

In terms of enhancements to a building's performance, the adoption of this system offers improvements to solar reflectivity (Gaffin et al., 2010) and stability of internal temperatures throughout the year, due to the addition of extra thermal mass (Santamouris et al., 2007), and also, reduction of heat flux (heat gain reduced by 70-90% in the summer and heat loss reduced by 10-30% in the (Oberndorfer et al., 2007) because of the favourable thermal properties of vegetation soil like latent heat loss (Wong et al., 2003). These aspects lead to the growing use of green roofs as natural thermal insulators. However, the installation of traditional thermal insulation layers is not expendable.

The natural thermal properties of green roofs are negatively affected by the level of moisture in the soil, which means that wetter soil is a poor insulator in comparison to dry (Wong et al., 2003). Nevertheless, due to the effects of evapotranspiration, it has been shown that heat can be drawn out of buildings in the case of wet soils (Lazzarin et al., 2005) which reveals the high potential of this system on passive cooling.

Concluding, the installation of green roofs shows great promise for cases of retrofitting as it can considerably improve energy savings in buildings with poor original insulation values. This system should also be considered in some cases with specific surrounding conditions where the importance of environmental aspects outcome the level of energy performance.

2.4.3. PASSIVE SOLUTIONS – GLAZED AREA

It is estimated that about 30% of the total heat losses are due to glazed areas, even though these areas have a fairly inferior quota on the building's envelope (Isolani, 2008). This is the consequence of the weaker thermal performances of the glass and frame elements on these areas, in relation to the remaining envelope. Agrela et al. (2011) concluded that the relation between the frame and glass areas, as well as the type of window (slider, hung, or fixed) will greatly influence the global transmittance value of the system. Aesthetics and functionality are often the main goals of these systems, however it is very important to comprehend the necessity of implementation of intelligent designs to these elements, as they can positively contribute to the indoor comfort of the occupants. Glazed systems' areas and orientation as well as the integration of shading devices, should be the primary aspects on the design of these elements. These, alongside with good performing glass panes and frame structures, result in highly energy efficient systems. Windows are one of the few constructive elements in which it is predicted a certification system following the guidelines of the Directive 2010/30/EU, labelling solutions by its energy efficiency (SEEP by ADENE).

2.4.3.1. Single pane windows with low emissivity glass

Single pane windows are the most inexpensive solutions for glazed areas in terms of installation cost due to its simple configuration. However, the exploration costs are mainly influenced by the emissivity of the glass sheet, the thermal conduction, and the thermal bridging aspects of the framing structure. The first one is determined by the type of glass used or the coating applied to said element. This means that low emissivity glasses (low-ε) will manifest lower heat flux through radiation. The principle behind this technology is the minimization of the amount of infrared and ultraviolet light that infiltrates through the glass pane, while not severely constraining the natural illumination of interior spaces. This product is achieved through the integration of an extremely thin coating on the surface of regular glass either through a pyrolytic process or the Magnetron Sputtering Vapor Deposition (MSVD) process. The first process consists in the fusion of the low-ε coating into the glass, while in production stage, conferring a strong bond and a very durable final product, usually named as a hard-coat low-ε glass. The second process refers to the application of the thin coating to pre-cut glass in a vacuum chamber ate room temperature. This type of coating is referred as soft-coat. Soft-coat low-ε glass tends to perform best at higher levels of demand as it offers the highest performing solar control, therefore, the integration of this product in situation of hot climates is advisable. This technology significantly improves the adaptability of single pane windows that otherwise would be very inefficient in typical configurations.

Lastly, the typical heat flux through conduction associated with the framing structure is influenced by the variety in used materials (metal, wood and PVC), which confer specific individual properties to the system. The importance of low conductance frames was studied and supported by (Gustavsen et al., 2008).

In terms of general energy performance, single pane windows are very limited configurations, and its application should be thoroughly considered only when the potential solar gains may balance out the characteristic lower resistance to heat loss of these windows. Also, the integration of single pane windows, without any solar protection or low-ε glass coating, in high solar radiation exposure façades will very likely contribute for the overheating of the indoor space in the summer.

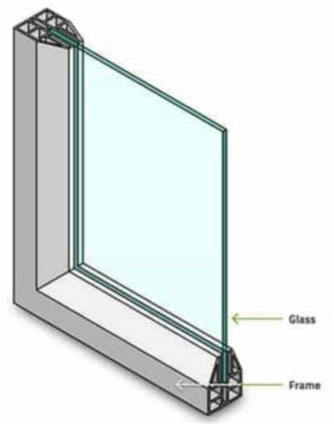


Figure 29 - Exemplification of a single pane window (from BRENNAN website)

2.4.3.2. Double pane windows

This system is composed by two panes of semi-transparent elements (glass sheets) with a spaced gap in between and limited, preferably, by a frame that should ensure the minimization of thermal bridging and infiltrations or leakages. Double pane windows, when appropriately designed, can deliver great performance in the thermal insulation of the glazed areas in a building's envelope while complying with the main objective of guaranteeing good indoor lighting.

The two sheets of glass promote a greater barrier to the outside elements and the obstruction of heat flux through conduction as the surfaces subjected to different temperatures are completely disconnected. Also, the air gap, with nominal widths of 6 or 16 mm, can be filled with other gases with better thermal properties than air (i.e. Argon, Krypton and Xenon) or even vacuumed, in order to minimize the phenomena of heat flux through convection and improving the global heat transmittance of the system. Finally, the frame concedes operability to the system, and isolates the glass panes from the involving elements. Ensuring the needed levels of airtightness is also important, complying with the minimal flow of fresh air in order to guarantee a salubrious indoor climate.

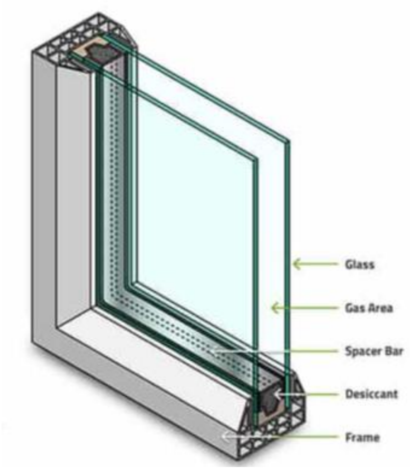


Figure 30 - Exemplification of a double pane window (from BRENNAN website)

Johal et al. (2011), studied the energy performance of glazed solutions in several European cities. They concluded that in cities like Madrid and Rome, which have essentially Mediterranean Climates, double pane windows with different orientations, can translate to significant energy gains in the cold season (solar gains being at the most about 8 times higher than energy losses depending on the specific configuration), reducing the required heating load.

2.4.3.3. Double frame windows

Mainly adopted in cases of refurbishments of existing buildings, this solution allows the improvement to the energy performance of originally single pane windows. It is typically composed by two sets of single glass panel windows separated by a minimum 50 mm spacing. The conjugate performance of these two sets must be determined and access compliance with regulation requisites. Aspects like airtightness should be thoughtfully considered in order to ensure the minimal air infiltration values. In terms of the global transmittance value, the integration of two sets of single glass panel windows will, as expected, reduce the U_w by half, in relation to the adoption of a typical single pane window (ITE 50). Smith et al. (2012) studied the performance of different secondary-glazing systems and concluded that these configurations' *R-value* were between 130% and 290% higher than the reference *R-value* of the typical single glazed window (with standard aluminium frame). Also, these results shown that these solutions could also be more performance advantageous in relation to generic double pane windows. Additionally, the adoption of low-cost solutions like the integration of a thin plastic film as the secondary glazing, would confer acceptable levels of performance. The incorporation of these systems, even though being considerably cheaper than other solutions and in some configurations with just as good levels of energy performance, can reduce the operability of the glazed areas. Plus, in cases of refurbishments, the deficient diagnosis of the outer window frame condition will result in an inappropriate solution with higher costs on further repair works.

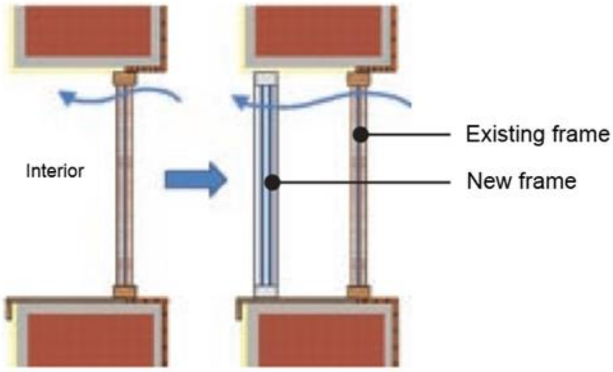


Figure 31 - Exemplification of an application of secondary glazing in a refurbishment work (ADENE, 2011)

2.4.4. PASSIVE SOLUTIONS – SOLAR PROTECTION

2.4.4.1. External blinds/shutters

External blinds are solar protection devices installed on the outside surface of glazed elements and can either be fixed or adjustable. There is an extensive variety of solutions in this category, diversified in the type of use (traditional shutters, roller shutters, etc.) and materials (aluminium, PVC, wood etc.). The adoption of this system as a direct influence on the reduction of global g-values and U-values of the windows. These blinds, when closed, improve the resistance to penetration of heat through the glazed areas during the day and the inverse phenomenon at night, keeping the interior climate warm. The integration of these elements on the outside reveals to be more beneficial for the global performance of the envelope as they keep most of the heat on the outside of the building, while, on the other hand, internal blinds are only put to work once the solar radiation is already inside resulting on the accumulation of heat in this space. Also, the fact that these blinds are often times adjustable, with various levels of shading, promotes the intelligent manipulation of these elements in favour of the indoor climate. Choi et al. (2017) studied the development of a shading device control algorithm and concluded that this implementation resulted in a 48% drop on energy consumption in relation to the same window with the same solar exposure only with no shading device.

2.4.4.2. Internal blinds

Internal blinds are solar protection devices installed on the interior side of glazed areas and, in this way, blocking the penetration of solar radiation towards the indoor surface, preventing unnecessary heat gains in the room and, additionally, increase the resistance to heat losses. In terms of thermal performance, Oleskowicz-Popiel and Sobczak (2014) concluded that the potential savings for the adoption of this system, in central European climate, is up to 33%, referring to a reduction of heat losses in the central part of a double-glazed window with the installation of internal blinds spaced by 20 mm from the inside surface of the inner glazed pane. In a configuration with low emissivity glass ($\varepsilon = 0{,}20$) the potential savings dropped slightly to 29%. Yoon et al. (2014) studied the difference in performance of both systems, internal and external solar protection, and multiple configurations of glazed areas through a sensitivity analysis and software simulation, in order to understand the effect these devices have on the global thermal performance of a building envelope. They concluded that aspects like the level of slat reflectance of the blind revealed opposite effects on both configurations, inducing a reduction of the cooling load of configurations with internal blinds while rising in configurations with external blinds as the level of reflectance increases. Internal blinds are often times more adjustable, in terms of the amount of light reaching the interior (i.e. venetian blinds), than other solar protection devices, as well as more lasting because they are not subjected to potential damage from outside elements.

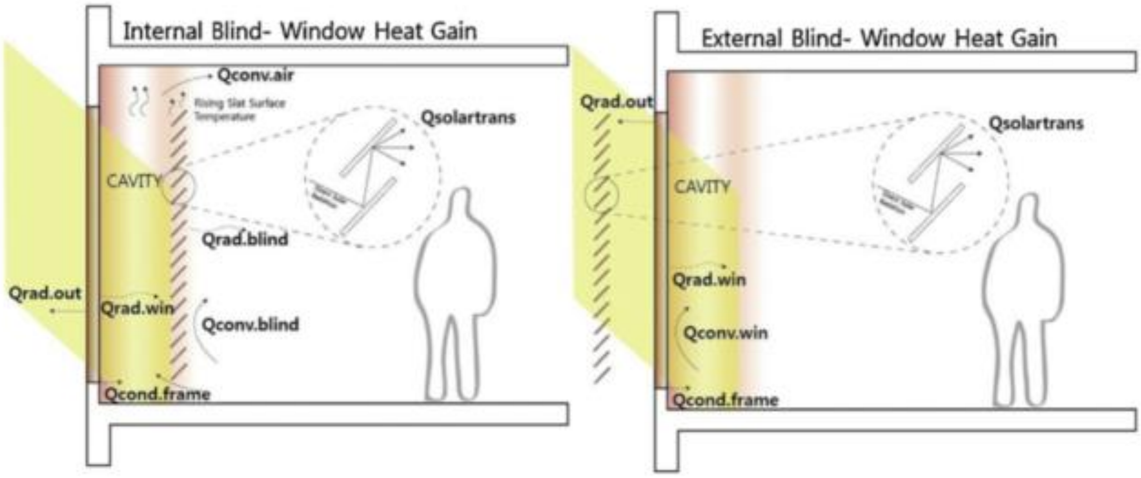


Figure 32 - Representation of heat gains through either solar protection devices, internal and external blinds (from (Yoon et al., 2014))

2.4.4.3. Overhang

Overhangs are horizontal shading devices that are installed in the external surface of the building's envelope and on top of glazed areas. These can either be a constructive element on project or installed later on. The main objective of these devices is to provide shade for the glazed areas bellow, and therefore, contributing for the reduction of excessive solar gains in the summer. The efficiency of this system is maximized in façades oriented to the south as it effectively blocks the solar radiation when the Sun is at its highest point in the summer while still allowing the potential for solar energy gains through the glazed area in the cold season. The impact of these solutions on annual cooling energy consumption tends to increase with the increase in the projection length.

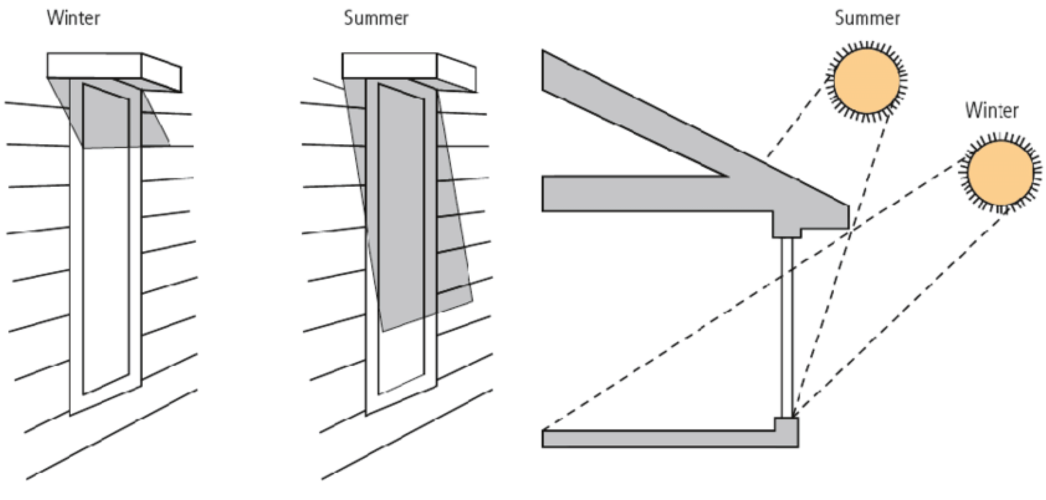


Figure 33 - Exemplification of the application of overhang on glazed areas, in summer and winter seasons (AKANDE et al., 2015)

2.4.5. Passive solutions – Natural ventilation

There are several systems for the implementation of natural ventilation on buildings which are based in different physics and thermodynamics principles. First, natural ventilation is defined as the renovation of the interior air for fresh outside air, through different configurations of openings on the envelope of the building. These systems are regulated by means of the natural flow of the wind or air flow due to pressure and temperature differences. The renovations of air are higher at night when the outside air temperature is significantly lower promoting a higher exchange of air between the inside and outside of the building. These phenomena are very important for climates like the Portuguese, as they take profit from thermal amplitudes during the day, specifically at night and early morning, complementing the more incapable response of thermal mass to the stabilization of air temperature inside in the cooling season. The global efficiency of these designs falls into the outside conditions, like topography, wind velocity, temperature, and air humidity, as well as the correct configuration of features on the building. Optimum configurations of these systems in aspects like orientation, opening's location, materials, and adjustability throughout the year, will significantly impact the need for cooling energy devices while delivering great air quality and comfort conditions to occupants.

In summary, natural ventilation solutions are very impactful on cooling loads in the summer and are cheaper and more environmentally sustainable than mechanical ventilation solutions.

2.4.5.1. Cross ventilation

Cross ventilation is a natural ventilation technique that is composed by two openings on opposite sides of the building's envelope, one intake and the other outtake, that promote the flow of fresh air inside. These installations can either be windows or wall louvers/vents, commonly of metallic finishing designs, that automatically or manually regulate the levels of intake of fresh air. This system is naturally powered by the pressure difference provoked by the wind, which generates positive and negative pressure zones on opposite sides of the building, and also, the difference of radiation exposures in both sides of the envelope. Karava et al. (2011) tested the predictability of internal airflow patterns and understood that the specific location and relative ratio of inlets and outlets are important parameters on the level of uncertainty on the system behaviour, particularly with high porosity walls (over 10%). In a proceeding paper, the actual ventilation performance of cross-ventilation solutions was studied in reference to single-sided ventilation solutions, which only predicts one opening in a room acting as both inlet and outlet feature (Park & Rhee, 2017). The authors concluded that the pursuance of parameters like volume flow rate, which estimates the exchange rate of the system, and the interpretation of local mean age of air (LMA) fields resulted in a more accurate calculation of this performance. Also, similar conclusions were achieved in this paper in reference to the previously mentioned study, where the positioning of openings manifested a significant importance on the volume flow rate, differing by 24% through several configurations. Overall, the dependability on fluctuant and uncontrollable elements like the wind is balanced by the cheapness of these projects.

2.4.5.2. Stack ventilation

Based in the stack effect principle, which is essentially takes benefit of air fluctuation due to the different density of rising warm air and inflated cooler air, stack ventilation systems offer a different take on natural ventilation of buildings. Typically composed by an inlet opening on the building's vertical envelope and a chimney outlet located at a higher relative level, usually on the ceiling. This configuration promotes the exhaust of warm air through the ceiling and the intake of fresh air through the inlet device due to the establishment of negative pressure zones in that area. This behaviour is proportionally affected by the gradient of outside and inside air temperatures. Wind can positively affect the exchange rate in stack ventilation systems by up to 350% in relation to windless conditions (Gladyszewska-Fiedoruk & Gajewski, 2012). However, wind can also be prejudicial to these systems as in certain wind direction and velocity combined with a low gradient on outside and inside air temperatures, can induce an inadequate functioning of the system.

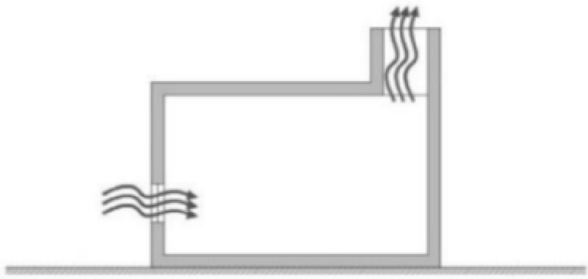


Figure 34 - Exemplification of a stack ventilation system, from (Mendonça, 2005)

2.4.5.3. Windcatcher

Windcatcher systems, although easily confused with previous systems due to the similar composition, have a different functioning principle. In this case, there is an inlet located at the top of the tower, considerably over the roof level and at a typically very windy height and is faced to the orientation of the strongest flow of air. Once captured, the wind is detoured to the building's inside through air ducts, inducing the renovation of the interior air. Consequently, the warmer air, as in the previous systems, ascends to an outlet feature, with opposite orientation and completely isolated from the inlet feature, and exits the building. Once again, buoyancy effect, due to the existence of different temperatures inside and outside, is an important factor to consider in this systems behaviour, however, the main factor of this solutions efficiency is related to the harnessing of intense wind streams. In places with no dominant wind streams, it should be considered the installation of multiple openings in the windcatcher tower, even though the increase in number of openings is directly associated with a negative effect in efficiency. In a study reviewing windcatcher technologies, concluded that the efficiency of the system is greatly affected by the shape and inclination angle of the windcatcher, where square and rectangular cross-sections combined with a 90º angle are the most efficient configurations (Saadatian et al., 2012). Also, the combination of solar chimneys and windcatcher systems promotes a higher efficiency solution, that can represent a cooling effect up to 15 ºC and double the air flow in the interior.

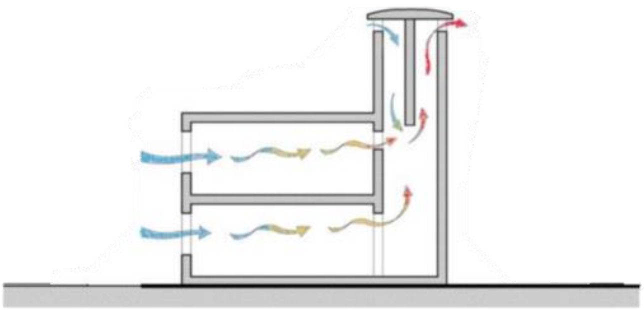


Figure 35 - Exemplification of a windcatcher system, from (Silva et al., 2020)

2.4.5.4. Solar chimney

The accumulation of heat from solar radiation in an air-chamber promotes the temperature gain of the air trapped in this area, provoking, through the stack effect, the exhaustion of warm air towards the rooftop chimney, while the intake flow, due to negative pressures in the inlet zone, concedes the renovation of the interior air. This system is highly affected by the levels of solar radiation exposure of the air-chamber and its permeability to solar gains. Therefore, the envelope of this space must be composed by large areas of glazed elements, with high solar factor values, and a dark absorbing surface, and it should also be taken into consideration the orientation of these elements, in order to attain optimum heat solar gains. However, once again, the effect of thermal buoyancy of the air is of great prevalence, as the presence of high outdoor temperatures at the rooftop level in induce a lower efficiency of the system. In summary, the key parameters for a solar chimney are its height, solar absorptance of the involving surfaces, air-chamber volume, and the solar transmittance of the envelope.

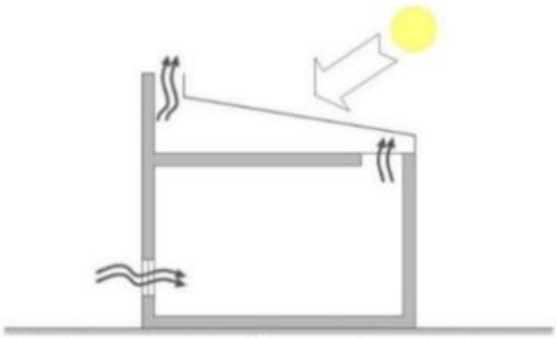


Figure 36 - Exemplification of a roof solar chimney system, from (Mendonça, 2005)

2.4.6. Active solutions – Solar powered technologies

2.4.6.1. Photovoltaic panels

The exploration of photovoltaic (PV) panels in the Portuguese residential sector as seen a large increase in the last 10 years, following a steady path to the projection of 13 GW centralized and decentralized use of this technology by 2050 (RNC 2050). This growth in the adoption of PV systems is justified by the continuous drop in general installation costs in this technology. The International Renewable Energy Agency (IRENA) has been releasing data showing that between 2010 and 2018, the decline on these costs was 74% and recent predictions appoint that this tendency will remain at least until 2050, when the average costs of installation will reach the range of 165 to 481 USD per kW of installation.

PV panels consist of interconnected smaller PV cells, which are essentially the base unit of this system and where the conversion of solar radiation to direct current (DC) electricity occurs. PV cells are made of semiconducting material, the most common being silicon-based (mono and polycrystalline). The second step in the process of transformation of solar energy into electricity consists in the conversion to alternating current (AC) through an Inverter device. The third step has two versions depending on the type of the PV system. In the case of a grid-connected system, the generated energy is conducted and sold to the public electricity grid, and this means that the building's consumption of energy is powered by the grid at night or in periods when PV panels cannot generate sufficient power. The second version relates to stand alone systems where electricity is usually stored into lithium-ion batteries, also known as solar batteries, meaning that the consumption of power in these households is completely autonomous. These solar batteries have a lifespan of 5 to 15 years contrasting with the typical lifespan of PV panels of 15 to 30 years meaning that these batteries will likely be replaced a few times throughout the exploration of these systems.

These installations can be categorised as fixed or tracking systems, the last being also known as sun-tracking PV systems which rely on mechanisms that direct the PV panels to the orientation of optimum solar exposure throughout the day, while the first, concerns free standing systems or either BPAV ("building attached photovoltaics") or BPIV ("building integrated photovoltaics"). The more traditional adoption of fixed PV systems is BPAV, which concerns to the installation of these systems into the building's structure. Alternatively, the incorporation of PV systems in a building's envelope, known as efficiency BPIV, substituting traditional constructive elements. Two examples are the installation of PV roof tiles placed directly over the roof structure and PV modules for skylights, which, overall, confer multi-functionality to these elements (good solution for thermal insulation of envelopes as well as electricity generation).

Figure 37 - Examples of installation of PV modules in skylight features (top left), PV tiles in solar roofs (top right), freestanding sun-tracking PV panels (bottom right) and a roof mounted PV panel (bottom left) (from "flexsolsolutions.com", npspower.com, and solarmagazine.com)

The general performance of PV systems is significantly influenced by certain aspects like exposure to solar radiation, shading conditions and spectral effects and is also inherently limited by the type of PV technology and the PV module temperature. Additionally, the market shows a range of 20-40% on the efficiency levels of these systems, which is result of a high investment in PV technology and promises to achieve even greater performance levels in the near future.

For the context of autonomous houses, the installation of PV technology will be the energy source of adequate heating and cooling systems. Therefore, it should also be taken into consideration the efficiency and the rentability of these systems.

2.4.6.2. Thermal solar collector

Another very interesting alternative predicted in the RNC 2050, in the hopes of turning profit from the extensive potential of solar energy technology, are thermal solar collectors or solar panels. In 2018, the market size of these systems was about 500 GW and it was predicted that by 2026 it would increase up to 768 GW representing a 50% growth on the market of solar panels. Nowadays, the estimate cost for each unit goes around 292 USD/m^2 to 4562 USD/m^2.

Solar panels have a similar purpose to PV panels, retrieve solar energy and convert it to usable energy for our everyday needs. However, while PV technology converts solar radiation into electricity, the principle in solar panel systems is to collect thermal energy from the sun and store that energy in a circulating fluid, frequently water, in order to be further used for heating purposes installations or even for domestic hot water. Hence, a typical thermal solar collector system is composed by two fundamental elements, a solar panel or solar collector, and a reservoir. This configuration is constant to both thermosyphon and forced circulation systems, which are the two most available systems in the market. While the first type benefits from the natural circulation of the fluid through the panel, as the reservoir is installed in a higher level than the solar panel, the second type forces the circulation of the fluid through the panel by means of a water pump, which is set to only pump the fluid from the reservoir, installed in a protected area, when the solar panel is at a higher temperature than the stored fluid. Therefore, the thermosyphon system is simpler and cheaper, however it is less energy efficient and more subjected to outside elements which confers a higher risk of endangering the system. The forced circulation system, while being more energy efficient due to the complex functionality, imposes a small energy consumption in order to serve its purpose.

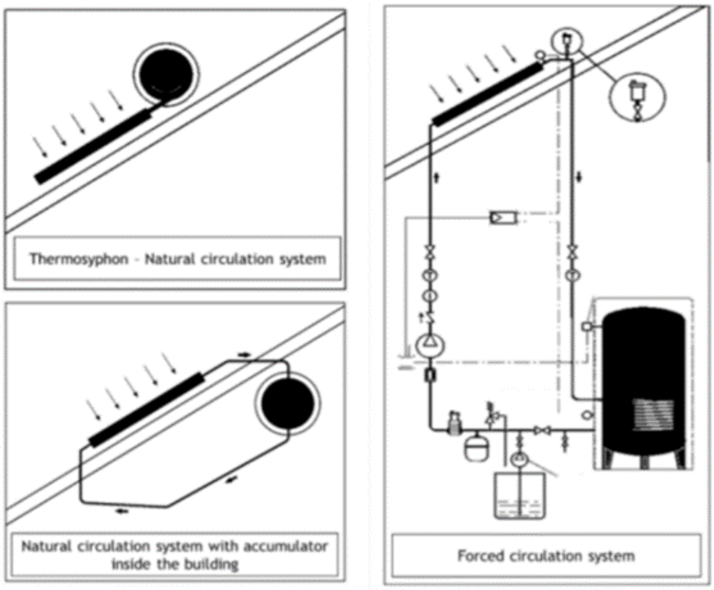


Figure 38 - Thermal solar collectors technologies, adapted from Caleffi (2006)

There are two types of solar collectors: non-concentrating (or stationary) and concentrating. These two diverge on the shape and the use of the surface area. The stationary collectors are defined by having the same area for intercepting and for absorbing solar radiation, whereas the concentrating panels have a concave reflecting surface that intercepts and focuses the solar radiation into a smaller absorbing area. This results in a higher radiation flux for the last system.

In terms of performance, as in PV panels, solar collectors are very dependable in conditions like solar radiation, shading conditions and the tilt and azimuth angles. Also, limitations to the global efficiency of the system are due to the composition of the solar panel and its materials, as well as if it has thermal insulation to prevent considerable heat losses.

2.4.7. Active solutions – Bioenergy heating systems

Bioenergy heating systems are very attractive and reliable option for the demands of the residential sector. The main principle of these systems is the combustion of organic matter, either from vegetal or animal origin, defined as biomass. The complete definition of biomass published in the Decree-Law 117/2010, states that it is the “biodegradable fraction of products, residues or debris from biological origin, deriving out of agriculture, forest exploration and springing industries, like fishing and aquiculture, as well as the biodegradable fraction from industry and urban residues”. Biomass fundamentally originates from plants, primary producers and a direct product of photosynthesis, an endothermic reaction aided by solar radiation, in which water and minerals in the soil and carbon dioxide present in the atmosphere are captured and broken into oxygen and sugar molecules. These products are key elements to the growth of plants and are also a very important energy source for animals that consume them. In the end, these energy components are stored in animal and vegetable matter and can be ultimately used as a great combustible material for the generation of heat and electricity or in the production of liquid, solid or gas biofuels.

Bioenergy currently represents more than 11% of global primary energy consumption and are a more sustainable fuel option than the traditional coal and fossil fuel for domestic hot water and heating purposes. However, the high moisture levels, low energy density, and the heterogeneity associated with this alternative incited a need for the upgrade of biomass fuels. This came to fruition through the introduction of pellet fuels to the market, which provoked the affirmation of biomass heating systems with no need for withdrawing from its original purpose of being a cleaner alternative to fossil fuels. In **Table 10**, the different types of marketable fuels are presented for the comparison of the thermal efficiency associated with each one of the solutions.

Table 10 - Fuel properties of wood chips, wood pellets, torrefied biomass, torrefied biomass pellets (TBP's), and bituminous coal, from (Almeida, 2019)

	WOOD CHIPS	WOOD PELLETS	TORREFIED BIOMASS	TBP'S	BITUMINOUS COAL
Moisture content *(%)*	30-60	7-10	3	1-5	5-10
Mass density *(kg.m^{-3})*	250-400	600-650	230	750-850	800-1000
LHV[7] *(MJ/kg)*	6-13	16.2	19.9	19-22	425
Calorific Value *(MJ/kg)*	1.7-3.6	4.5	5.5	5.2-6.2	7
Energy density *(MWh.m^{-3})*	0.7-0.9	3	1.3	4.2-5	5.6-7
Hygroscopic nature	HYGROSCOPIC	HYGROSCOPIC	HYDROPHOBIC	HYDROPHOBIC	HYDROPHOBIC
Biological degradation	YES	YES	NO	NO	NO

As shown in **Table 10**, the development and combination of the torrefaction and pelletizing techniques resulted in torrefied biomass pellets that have similar properties to bituminous coal, making it a very reliable clean alternative. However, this technology is still fairly new to the fuel market and for that reason it still has to prove itself as a reliable option regardless of its many good fuel properties and ground-breaking improvement in fuel sustainability.

[7] Lower Heating Value, also known as net calorific value.

3 CATALOGUE CONFIGURATION AND AUXILIARY ANALYSIS

3.1. INTRODUCTION

The main focus for this chapter is the introduction to the catalogue configuration. Composed by technical and economic information, these sheets compile a catalogue intended to support the study on the feasibility and compatibility of constructive solutions in the market in the intended project. For this reason, the information displayed in the catalogue will be brief and concise in favour of the ease of interpretation of all the intervenient parties on a housing project. However, further clarifications and developed data will be addressed in other chapters.

3.2. TECHNICAL DATA SHEET STRUCTURE

The structure of the technical data sheets included in this catalogue is organized according to the following information fields:

a) Identification of the solution
b) General description
c) Performance parameters
d) Solution's schematic
e) General observations
f) Economic assessment
g) Advantages and disadvantages
h) Recommendations

At the top of each technical data sheet, the identification field, as shown in **Figure 39**, will display the type of system (passive or active solutions) and the corresponding constructive area (external walls systems, roof systems, glazed areas, etc.) as well as the name of the addressed solution.

Passive Solutions - External Walls **ETICS – *External Thermal Insulation Composite System***

Figure 39 - Example of an identification field on the technical data sheet

The following information field concerns to the general description on the addressed solution, as shown in **Figure 40**. In this box, a brief explanation of the solution and the principle behind it will be presented.

General description:

Application of thermal insulation layer on the outside surface of external walls.

Figure 40 - Example of the general description field on a technical data sheet

Next, the performance parameter box will display the coefficients typically associated and/or the most relevant values related to the performance of each solution, as exemplified in **Figure 41**.

Performance parameters:

λ = 0,033 – 0.040 (W/m.K)

U* = 0,36 (W.m^{-2}.ºC^{-1})

Figure 41 - Example of the performance parameters field on a technical data sheet

The following section, the solution's schematic, shown on **Figure 42**, displays the typical configuration of the addressed solution

Solution's schematic:

There are two types of ETICS, bonded or mechanically fixed.

The typical system components are, in application order:

- adhesive
- thermal insulation material
- anchors (if required)
- base coat
- reinforcement mesh (usually fibre glass)
- finishing layer (finishing coat with key coat and decorative coat)

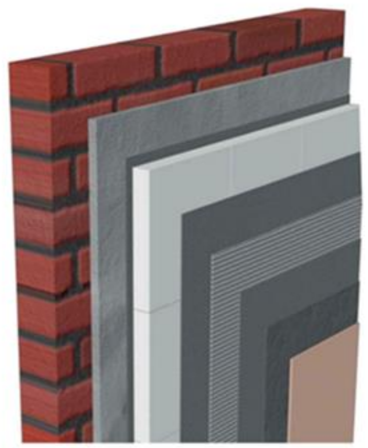


Figure 42 - Example of the solution's schematic field on a technical data sheet

The general observations box, illustrated in **Figure 43**, is a field destined for the presentation of additional information on the solution. It mainly consists of secondary details that are not essential to the understanding of the solution model but give a complementary insight.

General observations:

EPS, XPS, MW and ICB are the main materials for the thermal insulation layer

Figure 43 - Example of the general observations field on a technical data sheet

Next, the economic assessment field presents some brief information about the financial point of view of the addressed solutions, in **Figure 44**.

Economic assessment *

Estimated Investment Cost (€/m²)	Estimated Annual Energy Savings (€)	Return on Investment Period (years)
35 – 45	635 – 765	4

* These values are result from the economic assessment methodology developed in Chapter 3 page 42 and for the specific context of this work.

Figure 44 - Example of the economic assessment field on a technical data sheet

Finally, the bottom area of the technical data sheet presents some extra technical information like the advantages and disadvantages of the addressed solution and recommendations.

Advantages:
- Strong thermal mass
- Minimal thermal bridging

Disadvantages:
- Conflicts with the building's façade design
- Reduced shock resistance
- Risk for growth of biological colonies

Recommendations:
- Application of systems with European Technical Approval – E.T.A
- Qualified professional installation
- Application of anti-biological proliferation treatment

Figure 45 - Example of the extra information field on a technical data sheet

3.3. The Economic Assessment Methodology

3.3.1. Introduction to the Methodology

The economic standpoint of the addressed solutions presented in the respective technical data sheets, is a result of a technical and economic analysis of each individual solution's contribution to the energy efficiency of a habitable space. Economic indicators like the level of expected annual energy savings and the return-on-investment period give a fair insight of the efficiency of each presented solution and are of the upmost importance for the developer and project managers study on the most viable solution to pursue. Therefore, an economic study was conducted, where it was assessed the impact of each system on the annual energy balance of a hypothetic base model residential building.

After the general definition of the base model for the hypothetical residential building in this economic study the next step is to assess the energy balance of this building. This was determined with the aid of a spreadsheet program developed by ITECONS, a non-profit association recognised as a public utility institution dedicated to the promotion of scientific knowledge in areas like construction, energy, environment, and sustainability. The main objective of this digital tool is to aid building developers on the process of energy certification and pre-certification. Thus, when inputted with the necessary information on the specific building, this tool is configurated to automatically return the global energy performance of the building and the verification of the minimum requisites following the guidelines of the SCE, updated by the Decree-Law 101-D/2020, which concerns to all buildings developed after the 1st of July 2021.

3.3.2. Defining the General Conditions of the Base Model Building

This building consists of a one room single family residential building, as described in **Table 11**, and implanted in the city of Porto (the selection of the building's location followed no relevant criterion).

Another important general information to include is the climate zone data, shown on **Table 12**, which is automatically determined by the software's climate data base upon the selected location input.

Table 11 - Description of the base model residential building

Geographic location	City:	Porto, Portugal
	Altitude:	0 m
	Distance to coast:	Less than 5 km
	Surrounding conditions:	No obstacles, very exposed area
Building Description	Number of rooms:	1 (T0)
	Useful pavement area:	100 m²
	Ceiling height:	3,5 m
	Number of storeys above ground level:	1
	Number of storeys below ground level:	0

Table 12 - Climate data of the city of Porto

Climate data of the city of Porto			
Climate winter zone	I1	Climate summer zone	V2
Average outside temperature in winter (°C)	10,6	Average outside temperature in summer (°C)	20,9
Extent of the heating season (months)	6,0	Extent of the cooling season (months)	4,0

3.3.3. Defining the external envelope of the base model building

Once the input of the general conditions of the base model residential building, as described in **Table 11** and **Table 12**, is finalized, the spreadsheet advances to the technical definition of the external envelope of the building, described in **Table 13**. The envelope was idealized to be representative of a poor energy performance building, with no integration of thermal insulation, and non-compliant with the updated minimum performance requisites. The collected performance parameters like the *U-value* and *g-value* of each solution are retrieved from the "*ITE 50 – U-values of Buildings Envelope Elements"* publication.

Table 13 - Technical description of the external envelope of the base model building

Constructive element	**Description of solution**	**Solution's parameters**
External walls	Four masonry walls of concrete brick (20 cm) with traditional plaster layer on both surfaces (2 cm)	Solution thickness: 24 cm Total perimeter: 40 m Total area: 140 m² ***U-value*** = 1,9 W/(m².°C)
Roof	Light auto-protected flat roof with waterproofing membrane, light concrete shape layer (10 cm), reinforced concrete slab (20 cm), and traditional plaster layer on the inside surface (2 cm)	Solution thickness: 32 cm Total area: 100 m² ***U-value*** = 1,6 W/(m².°C) (upwards heat flux) ***U-value*** = 1,4 W/(m².°C) (downwards heat flux)
Ground floor	Laminate wood flooring (2 cm) above shape layer (4 cm) and solid concrete slab (15 cm)	Solution thickness: 21 cm ***U-value*** = 2,5 W/(m².°C) (downwards heat flux) ***U-value*** = 3,1 W/(m².°C) (upwards heat flux)
Glazed areas	Two 250x200 cm² single glazed windows with PVC framing	Disposition of glazed areas: South and North façade Total area: 10 m² ***U-value*** = 4,9 W/(m².°C) ***g-value*** = 0,88
Entrance Door	Wood door 80x200 cm²	Total area: 1,60 m² ***U-value*** = 2,7 W/(m².°C)

Considering the previously presented information, the procedure for the calculation of the building's energy performance must be adapted to the stipulated methodology associated with each of the constructive elements. The first subcategory of the external envelope is external walls. Here, the definition and description of the adopted solutions is inputted, as shown in **Table 14**. Also, further information on the involvement of plane thermal bridging is requested, predicting a contribution of eventual adjacent constructive elements like columns and beams on the global thermal transmittance parameter of the solution. Thus. as predicted in Table I.06 from the Ordinance Nº 349-D/2013, whenever the plane thermal bridging on the external envelope fabric is undefined, as a simplification, the respective *U-value* is increased in 35% of the original value. Additionally, **Table 15** relates to the properties of the solution, like the respective orientation, area, area to deduct and colour of each wall.

Table 14 - Definition and description of the adopted external wall solution on the base model building

Identification of the type of solution	Solution type	Detailed Description	U-value Solution (W/m^2.°C)	Existing or amplified zone?	Subject to renovation?	Solution involves plane thermal bridging?
EW1	External wall – Type 1	Masonry walls of concrete brick (20 cm) with traditional plaster layer on both surfaces (2 cm)	1,90	Existing	No	Yes

Table 15 - Further information on the designated solution for external walls in the base model

Designation of the solution	Orientation	Area (m^2)	Area to deduct (glazed area, plane thermal bridging...) (m^2)	Colour	Ventilated façade?	U-value Solution (W/m^2.°C)	Effective area (m^2)	U reference (W/m^2.°C)
EW1	South	35,00	5,00	Medium	No	1,90	30,00	0,50
EW1	North	35,00	5,00	Medium	No	1,90	30,00	0,50
EW1	East	35,00	1,60	Medium	No	1,90	33,40	0,50
EW1	West	35,00	0,00	Medium	No	1,90	35,00	0,50

Next, the assessment of the shading conditions is requested. This base model did not contemplate obstructions or solar protection devices, as presented in **Table 16**.

Table 16 - Description of the shading conditions on the designated solution for external walls in the base model

Designation of the solution	Horizontal obstruction device α °	Left vertical obstruction device β_{left} °	Right vertical obstruction device β_{right} °	Shading in cooling season
EW1	-	-	-	No shading
EW1	-	-	-	No shading
EW1	-	-	-	No shading
EW1	-	-	-	No shading

Next subcategory concerns to the roofing solution, which is similarly detailed in **Table *17*** and **Table *18***.

Table 17 - Definition and description of the adopted roofing solution on the base model building

Designation of the Solution	Solution Type	Detailed Description	U-value upwards heat flux (W/m^2.˚C)	U-value downwards heat flux (W/m^2.˚C)	Existing or amplified zone?	Subject to renovation?	Solution involves plane thermal bridging?
ER1	Roof Solution - Type 1	Light auto-protected flat roof with waterproofing membrane, light concrete shape layer (10 cm), reinforced concrete slab (20 cm), and traditional plaster layer on the inside surface (2 cm)	1,60	1,40	Existing	No	Yes

Table 18 - Further information on the designated solution for roofing in the base model

Designation of the Solution	Total Area (m^2)	Colour	Layer with ventilated air gap?	U-value upwards heat flux (W/m^2.˚C)	U-value upwards heat flux (W/m^2.˚C)	U-value reference (W/m^2.˚C)
ER1	100,00	Medium	No	1,60	1,40	0,40

Further on the spreadsheet, the definition of the properties of the flooring system is introduced. In this case, the floor system is implanted in direct contact with the soil, which implies the calculation of the effective *U-value* of this system. First, the characteristic dimension of the flooring solution in contact with the soil (*B'*), determined through equation (10). Then, the characteristic thermal transmittance coefficient of flooring solutions in contact with the soil (U_{bf}) is determined through the following **Table 19**.

$$B' = \frac{A_{p,ground}}{0{,}5 \times P} \ [m] \qquad (10)$$

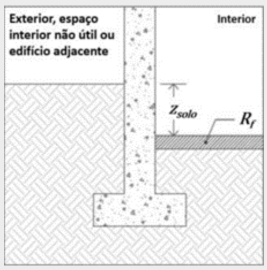
$A_{p,ground}$ – Useful interior pavement area, directly in contact with soil [m²]

P – Exposed perimeter, defined by the total development of exterior walls [m]

B' – Characteristic dimension of the flooring solution in contact with the soil [m]

Table 19 - U_{bf} of flooring solutions in contact with the soil, with continuous insulation or without insulation

B'	**Z_{soil} ≤ 0,5 m**			
	R_f [(m².°C)/W]			
	0,5	**1**	**2**	**≥ 3**
3	0,65	0,57	0,32	0,24
4	0,57	0,52	0,30	0,23
6	0,47	0,43	0,27	0,21
10	0,35	0,32	0,22	0,18
15	0,27	0,25	0,18	0,15
≥ 20	0,22	0,21	0,16	0,13



Note: For floor solutions with Z_{soil} ≤ 0,5 m and R_f < 0,50 [(m².°C)/W], U_{bf} = 1,15 × $U_{R_f=0,50}$ [W/(m².°C)]
R_f – Thermal resistance of all flooring solution layers, excluding superficial thermal resistances [(m².°C)/W]

In this case, *B'* = 5 m and R_f = 0,24, and hence Z_{soil} = 0 m and $R_f \leq 0{,}5$, the formula $U_{bf} = 1{,}15 \times U_{R_f=0{,}50}$ is valid. Therefore, through linear interpolation, $U_{bf} = 0{,}60$.

Table 20 - Definition and description of the adopted ground flooring solution on the base model building

Designation of the type of solution	Type of solution	Detailed Description	Area (m^2)	U-value ($W/m^2.^{\circ}C$)	U-value Reference ($W/m^2.^{\circ}C$)
GF1	Ground floor - Type1	Laminate wood flooring (2 cm) above shape layer (4 cm) and solid concrete slab (15 cm)	100	0,60	0,50

Table 21 - Further information on the designated solution for the ground floor in the base model

Designation of the type of solution	R_f ($m^2.°C/W$)	Exposed Perimeter P (m)	Exposed wall thickness w (m)	Perimetral insulation?
GF1	0,24	40	0,24	No

Finalising the definition of the opaque envelope, the performance parameters of the entrance door is inputted to the software as displayed in **Table 22**.

Table 22 - Definition and description of the adopted entrance door solution on the base model building

Designation of the type of solution	Type of solution	Detailed Description	Area (m^2)	Default Solution?	Type of door	U-value ($W/m^2.^{\circ}C$)
ED1	Entrance Door - Type 1	Wood door 80x200 cm²	1,60	Yes	Wood	2,70

Once the external envelope is completely defined, the calculation of the thermal inertia of the building is the next step.

$$I_t = \frac{\sum_i M_{si} \,.\, r_i \,.\, S_i}{A_p} \left[\frac{kg}{m^2}\right] \qquad (11)$$

I_t – Useful superficial mass per square meter of useful interior pavement area [kg/m²]
M_{si} – Useful superficial mass of the element *i* [kg/m²]
r_i – Reduction factor of the useful superficial mass of the element *i*
S_i – Area of the interior surface of the element *i* [m²]
A_p – Useful interior pavement area [m²]

In order to determine the value of each external envelope element's useful superficial mass, first step is the definition of the boundary conditions of each element:

a) EL1 – Elements of the external envelope with exterior-interior boundary conditions and no thermal exchanges
b) EL2 – Elements with ground boundary conditions
c) EL3 – Elements of the indoor environment

Therefore, the roof solution and the external walls solution integrate the type EL1 while the ground slab solution integrates the type EL2. Secondly, the formula for the calculation of the M_{si} of each type of element is as it is displayed in the following **Table 23** and **Table 24**.

Table 23 – Elements of type EL1

No thermal insulation layer nor air gap	Air gap and no thermal insulation	With thermal insulation layer
$M_{si} = \frac{m_t}{2}\ [kg/m^2]$ m_t – Total mass of the element [kg/m²]	$M_{si} = m_{pi}\ [kg/m^2]$ m_{pi} – Inner pane mass [kg/m²]	$M_{si} = m_i\ [kg/m^2]$ m_i – Inner pane mass until the thermal insulation layer [kg/m²]
$M_{si} \leq 150\ kg/m^2$		

Table 24 – Elements of type EL2

No thermal insulation layer	With thermal insulation layer
$M_{si} = 150\ kg/m^2$	$M_{si} = m_i\ [kg/m^2]$ m_i – Mass of the element from interior until the thermal insulation layer [kg/m²] $M_{si} \leq 150\ kg/m^2$

Lastly, the useful superficial mass reduction factor (r_i) concerns the type of finishing layer on the interior surface of the outer shell of the building, which essentially influences the heat absorption capacity of each element. Therefore, the higher the thermal resistance of the coating layer the lower is the capacity for the element to store heat in itself. This relation is interpreted in **Table 25**.

Table 25 - Useful superficial mass reduction factor

Coating resistance [(m².°C)/W]	r_i
R < 0,14	1
0,14 ≤ R ≤ 0,30	0,5
R > 0,30	0

As a result of this procedure, the thermal inertia of a building is distinguishable through the following conditions:

a) **Weak** – $I_t < 150$
b) **Medium** – $150 \leq I_t \leq 400$
c) **Strong** – $I_t > 400$

On the case of this base model, **Table 26** presents the presents the summary of the previously detailed calculation.

Table 26 – Summary of thermal inertia class definition of the base model building

Type of Element	Area (m²)	Total Mass (kg/m²)	Msi	r	Si*Msi*r
EL1					
EW1	128,40	136,00	136,00	1,00	17462,40
ER1	100,00	382,00	150,00	1,00	15000,00
EL2					
GF1	100,00		150,00	1,00	15000,00
				I_t	474,62
				Thermal Inertia class	Strong

Following the opaque envelope, the external glazed areas is the next element to define. **Table 27** sets the general characteristics of the solution for the glazed areas and table goes into further detail on the technical properties of this element. For this base model, the total glaze area is 10 m² which amounts to 10% of the useful pavement area (A_p), complying with the regulation minimum of 5%.

Table 27 - Definition and description of the adopted glazed area solution on the base model building

Designation of the type of solution	Type of solution	Detailed Description	Type of solar protection	Existing or amplified zone?	Subject to renovation?
GA1	Glazed Area - Type 1	Two 250x200 cm single glazed windows with PVC framing	No solar protection	Existing	No

Table 28 - Further information on the designated solution for the glazed area in the base model

Designation of the type of solution	Uwdn (W/m².°C)	g⊥,vi	Glass type	Glazed fraction Fg	U-value Reference (W/m².°C)	Area (m²)
GA1	4,90	0,88	Single	0,65	2,80	10,00

Designation of the type of solution	Orientation	Glazed Area (m²)	Glazed area facing the façade?
GA1	South	5,00	Yes
GA1	North	5,00	Yes

Finishing the analysis of the external envelope, the final step consists of the determination of the heat losses due to linear thermal bridges. These relate to the concentration of heat flux that occurs through the connection of constructive elements with different geometry or even different thermal properties. The considered values in the study of this base model relates to the values of **Table 29**, which is predicted in regulation for the specific situation of existing buildings and assuming a non-insulated envelope. Consequently, the practical results of these applications are displayed in **Table 30**.

Table 29 - Linear thermal transmittance coefficient default value

Type of linear connection	ψref (W/m.°C)
Façade with ground floor Façade with exterior floor or over non-heated space Façade with roof Façade with intermediate level floor Façade with balcony	0,70
Two vertical walls in salient angle	0,50
Façade with window frame Shutter box zone	0,30

Table 30 - Practical linear thermal bridges values on the base model building

Linear Thermal Bridges	Linear development B m	Ψ W/m.°C	Ψ.B W/°C
Façade with ground floor	40,00	0,70	28,00
Façade with roof	40,00	0,70	28,00
Two vertical walls in salient angle	14,00	0,50	7,00
Façade with window frame	18,00	0,30	5,40
		TOTAL	68,40

3.3.4. DEFINING THE INTERIOR ENVIRONMENT OF THE BASE MODEL BUILDING

For this energy balance assessment study, the interior environment of the base model residential building was considered to not significantly influence the energy balance of the building, in order to simplify the proposed methodology. This will result on a not as accurate simulation of the expected energy balance but will otherwise give a reliable expectation of the general building efficiency on the proposed conditions. Therefore, the interior space was defined as one global habitable space, resulting in one single thermal zone.

3.3.5. DEFINING VENTILATION CONDITIONS OF THE BASE MODEL BUILDING

Once the external envelope is completely defined, the ventilation conditions of the habitable space have to be appointed. The ventilation performance of the building is directly influenced by the outside climate, general implantation conditions, the external envelope permeability, and the integrated ventilation systems.

The outside climate influence on the ventilation mechanics of the building is defined through the principle of stack effect. The difference between the outside and inside temperature, on the coldest month of the heating season, induces a hot air flux denominated as buoyancy. This phenomenon originates a difference of pressure (ΔP) between the two environments which results on the exchange of hot air, seeping through the envelope, and fresh air leaking into the indoor space.

The general implantation conditions of the building are defined by the level of isolation and the location of the building. These conditions will affect the proposed wind load levels on further calculations.

In order to simplify the base model in terms of the calculation of the annual energy balance, it was stipulated that the building is completely isolated, vertical obstacles on the nearest surroundings were not considered. Hence, the level of protection of the façades to the wind action is considered to be unprotected. Also, the height of the façade will differentiate the pressure coefficient (C_p) value on the calculation of wind pressure on the building's fabric.

The building is located, as previously defined, in a less than 5 km distance to coast zone, corresponding to the Region B classification on the regulation, which will greatly influence the wind speeds for the calculation of the wind loads acting on the building's façades. This wind load will be considered on all of the external envelope as the building's fabric is completely exposed.

Furthermore, the considered ventilation system for this model base buildings is a natural ventilation system. In this version, a simpler configuration is accounted, and then further solutions will be approached in the following versions, and the impact of these implementations. Thus, on this base model there are no stipulated openings on the fabric nor air ducts, hence the ventilation of the space is solely result of the permeability of the external envelope, simulating the harshest ventilation conditions.

The measurement of the characteristic permeability of the external envelope is defined by the value n_{50}, obtained by the pressurization test, with the predicted guidelines in EN 13829 norm. Equation (12) calculates the air flow due to the global permeability of the envelope ($q_{v,n_{50}}$), defined by the pressure test n_{50} and proportioned by the habitable space volume ($A_p \, . \, P_d$) and the pressure differential between the indoor and outdoor environment (ΔP).

$$q_{v,n_{50}} = n_{50} \, . A_p \, . P_d \, . (\frac{\Delta P}{50})^{0,67} \quad \left[\frac{m^3}{h}\right] \qquad (12)$$

However, in cases where the n_{50} test is not predicted, the main cause of air insufflation/leakage is the characteristic permeability of the window framing and the eventual shutter boxes. This is the case for this base model assessment, which is determined by equation (13). In this calculation, the air flow due to the window permeability ($q_{v,window}$) is reliant on the permeability class of the window (W), stipulated on the manufacturer technical information, and the window area (A_W).

$$q_{v,window} = W \, . A_W \, . (\frac{\Delta P}{100})^{0,67} \quad \left[\frac{m^3}{h}\right] \qquad (13)$$

Additionally, the permeability of the incorporated roller shutter boxes is also predicted in regulation and defined through equations (14) and (15)**,** which are respective to different airtightness levels. The permeability class of a shutter box is established on several conditions and is distinguished between two main classes: low permeability class and high permeability class. Low permeability class is established for cases where: the permeability test for a pressure difference of 50 Pa results in a tested air insufflation rate of less than 0,63 $m^3/(h.m)$; the permeability test for a pressure difference of 100 Pa results in a tested air insufflation rate of less than 1 $m^3/(h.m)$; the roller shutter strap establishes the only communication between the indoor environment and the roller shutter box; the shutter box establishes a communication with the indoor environment, while presenting an adequate sealing. For all the other situations not predicted in the previous statement, the roller shutter box is established as a high permeability class.

$$q_{v,shutter\ box,low} = 1 \, . \left(\frac{\Delta P}{100}\right)^{0,67} . \, 0,7 \, . A_W \quad \left[\frac{m^3}{h}\right] \qquad (14)$$

$$q_{v,shutter\ box,high} = 10 \, . (\frac{\Delta P}{100})^{0,50} . \, 0,7 \, . A_W \quad \left[\frac{m^3}{h}\right] \qquad (15)$$

Another important parameter to consider for the calculation of heat loss due to ventilation, are the minimum fresh air flow rates imposed by regulation. According to the ordinance Nº 12, article 6.º from the Decree-Law Nº 101-D/2020, every new building, or existing building subjected to great renovation works, must present an hourly air renovation rate (R_{ph}) equal or greater to 0,5 renovations per hour. Furthermore, it is advisable to develop housing ventilation projects considering a factor of 0,5 air renovations per hour for the heating season, minimizing the potential for heat loss due to obligatory ventilation necessities, and 0,6 renovations per hour for the cooling season.

In order to calculate the interior pressure and the respective ventilation air flow rates, the simplified method is envisioned in regulation as the principal methodology, defined in (16), for cases of spaces where the production of pollutants or presence of combustion equipment are not expected.

$$\sum_i q_{v,window}(\Delta p_i) + \sum_i q_{v,shutter\ box}(\Delta p_i) + \sum_i q_{v,opening}(\Delta p_i) + \sum_i q_{v,air\ duct}(\Delta p_i) + \sum_i V_{fi} = 0 \qquad (16)$$

$q_{v,window}(\Delta p_i)$ – Air flow rate due to the window permeability for the pressure difference Δp_i [m³/h]
$q_{v,shutter\ box}(\Delta p_i)$ – Air flow rate through the shutter box for the pressure difference Δp_i, including low and high permeability [m³/h]
$q_{v,opening}(\Delta p_i)$ – Air flow rate through ventilation openings for the pressure difference Δp_i [m³/h]
$q_{v,air\ duct}(\Delta p_i)$ – Air flow rate through ventilation air ducts for the pressure difference Δp_i [m³/h]
V_{fi} – Air flow rate through mechanical ventilation equipment [m³/h]

In the end, once all these components are defined and inputted into the software, the final configuration, and the final returned results for the ventilation of the base model building are summarized in **Table 31** and **Table 32**.

Table 31 - Summary table of the final configuration for the ventilation assessment on the base model building

Protection of the building	Height of the façade [m]	Average local wind speed [m/s]	Exposure level of the building fabric	Average outside temperature of the coldest month [°C]	Pressure coefficient (C_p)		Dynamic pressure due to wind load [Pa]	Pressure difference due to Stack effect (Δ*P*) [Pa]
Unprotected	3,5	4,88	Very exposed	10,60	Windward Façades	0,5	7,25	8,7
					Leeward Façades	0,7	-10,15	-8,7

Table 32 - Summary table of the final results of the ventilation assessment on the base model building

Interior pressure [Pa]	Air flow rate [m³/h]	Estimated R_{ph} [h⁻¹]	Estimated n_{50}
-1,45	97,36	0,28	1,8

3.3.6. Energy balance of the base model building

The energy balance of the base model building, adopted for the purpose of this economic assessment, only concerns the heating and cooling energy necessities, as the remaining components of the annual global primary energy necessities (N_t; N_{tc}) are not relevant for this catalogue. Thus, **Table 33** and **Table *34*** display the returned values from the ITECONS spreadsheet, for the energy necessities in the heating and cooling seasons respectively, calculated through the input of all the previously presented components. It must be noted that these results relate to the regulation determined nominal conditions, adopting the fixed values of 18 °C for the interior temperature on the heating season and 25 °C for the interior temperature on the cooling season. Only the final values will be presented in order to economize the extensiveness of this work.

Table 33 – Summary table of the returned values for the heating season of the base model building

$Q_{tr,i}$ [kWh/year]	$Q_{ve,i}$ [kWh/year]	$Q_{gu,i}$ [kWh/year]	N_{ic} [kWh/m²]
19291,57	1570,23	4281,94	165,80
$Q_{tr,i\ REF}$ [kWh/year]	**$Q_{ve,i\ REF}$ [kWh/year]**	**$Q_{gu,i\ REF}$ [kWh/year]**	**N_i [kWh/m²]**
6127,85	1570,23	2065,84	56,32

Table 34 – Summary table of the returned values for the cooling season of the base model building

$(1-\eta_v)$	$Q_{g,v}$ [kWh/year]	N_{vc} [kWh/m²]
0,11	7668,55	8,64
$(1-\eta_{v\ REF})$	**$Q_{g,v\ REF}$ [kWh/year]**	**N_v [kWh/m²]**
0,17	5385,20	9,13

On a brief analysis of these results, the level of efficiency of this building is very low as the global necessities greatly surpass the reference values. As expected, the heat losses through transmission in the heating season ($Q_{tr,i}$) parcel is the main focus point on the underperformance of this base model building, outcoming the reference value by 314,8%. Therefore, the integration of solutions with thermal insulation on the external envelope have very high potential for a substantial positive impact on the annual useful energy heating necessities (N_{ic}) of the building. On the other hand, the useful heat gains ($Q_{gu,i}$) more than doubles the reference value, positively contributing to the reduction of the energy necessities in the heating season. This is mainly due to the optimal solar radiation exposure on the south oriented façade, which the 5 m² window takes a very big "profit" from. The heat losses due to air renovation ($Q_{ve,i}$) will always match the reference value as long as no heat recovery systems are integrated in the building.

Concerning the performance of the building during the cooling season, the gross heat gains parcel ($Q_{g,v}$), in contrast with the heating season, assumes a prejudicial factor to the cooling necessities (N_{vc}) due to the potential for excessive solar gains through the envelope, and specially the glazed areas. Therefore, the integration of better performing window solutions would significantly impact the energy balance of the building as these represent about 23% of the gross solar gains ($Q_{sol,v}$), while also representing about 4% of the total building envelope area. Fortunately, the high heat gain utility factor (η_v), due to the strong thermal inertia of the building, is able to maintain the value of cooling necessities just under the limit.

3.3.7. Solutions for the improvement of the energy balance of the base model building

After taking into consideration the previously presented results of the global energy balance of the base model building, some conclusions arose: the building would strongly benefit from a better performing building fabric; the existing windows, while positively contributing to the mitigation of heating necessities, have also a disproportionate contribution for solar gains in the cooling season; the integration of ventilation systems would give a higher control over the air-tightness of the building; the need for a feasibility study on the integration of renewable energy sources. Therefore, the proposed methodology for the assessment of the efficiency of the collected solution, stands on the individual integration of each solution the base model building, and through the returned energy balances from the ITECONS spreadsheet, understand the global impact of each improvement, acknowledging their level of rentability.

In order to give a better insight of the global efficiency of each system (ETICS, internal insulation, etc.) it is predicted, whenever it is compatible with the system, the integration of different levels of quality of the solution.

For the case of the integration of passive solutions on the external envelope, 5 levels of quality are tested as shown in the **Table *35***.

Table 35 – Levels of quality of the integrated solution in function of the U-value limits

Level of quality	*U-value* limit
N0	Base model solution
N1	$U_{N1} = U_{REF}$
N2	$U_{N2} = 0{,}75 \times U_{REF}$
N3	$U_{N3} = 0{,}60 \times U_{REF}$
N4	$U_{N4} = 0{,}50 \times U_{REF}$

For the integration of each individual system, the process for the calculation of the energy necessities is very similar to the presented from the base model building, with some adaptations. Only relevant information on the adaptation of the process of the integration of a specific solution will be mentioned. On another note, it should be mentioned that the ground floor system was not altered as the base model building energy balance showed that the heat losses through the flooring solutions are not as troublesome as on the rest of the external envelope, since the soil typically acts like an insulation layer, and the structure is not exposed, thereby, not as affected by the outside climate.

On the external walls systems, the major adaptations in relation to the base model building process, were:

- ETICS – Recalculation of the thermal mass of the building; adjustment of the practical thermal linear transmission coefficients; change the global thickness of the wall solution in contact with the ground floor for each level of solution.
- Internal insulation – Recalculation and downgraded thermal mass class of the building; adjustment of the practical thermal linear transmission coefficients; change the global thickness of the wall solution in contact with the ground floor for each level of solution.
- Double wall façades – Recalculation of the thermal mass of the building; adjustment of the practical thermal linear transmission coefficients; solution divided into two different configurations, double wall with partially filled air gap and double wall with filled air gap; on the configuration of partially filled air gap, the solutions were tested for different levels of ventilation: weakly ventilated and no ventilation; change the global thickness of the wall solution in contact with the ground floor for each level of solution.
- Ventilated façade – Recalculation of the thermal mass of the building; adjustment of the practical thermal linear transmission coefficients; solution divided into two different configurations relative to the level of ventilation: strongly ventilated air gap and weakly ventilated air gap; change the global thickness of the wall solution in contact with the ground floor for each level of solution.

For the roofing solutions, the major adaptations in relation to the base model building process, were:

- Inverted roof – Recalculation of the thermal mass of the building.
- Pitched roof with insulation on top of the ceiling slab - Recalculation of the thermal mass of the building; input of the performance parameters on the interior roof systems due to the creation of a secondary zone (unhabitable zone) in the loft area; specification of the level of ventilation on the loft area (strongly ventilated).
- Pitched roof with insulation at the rafter level - Recalculation of the thermal mass of the building; define the level of ventilation on the air gap between the insulation layer and the external cladding.

For the glazed solutions, there were no major adaptations in relation to the base model building process. However, for the integration of the solar protection devices coupled with the single glass window, the parameters related to the shading device had to be inputted to the spreadsheet, and thus, the calculation for the corrected solar factor (g_{tot}) and transmittance coefficient of the window (U_{wdn}), due to the influence of the activated solar protection. Also, the levels of quality of the tested solutions were dependant on the type of shading device instead of the *U-value* limits.

Therefore, to economize the extensiveness of this work the final results of the integration of the several passive solutions for the integration on the external envelope, are summarized in **Table 36** and **Table 37**

Table 36 - Summary table of the energy balance for each integrated passive solution – window and shading device

System	Description of the solution	Level of quality	Type of solar protection device	U_{wdn} (W/m².°C)	g_{tot}	Cost of investment (€)	N_{ic} (kWh/m²)	N_{vc} (kWh/m²)
Glazed areas (U_{REF} = 2,80)								
-	-	N0	-	4,9	0,88	362,5	165,8	8,64
Single glass window + External Solar Protection	Windows composed by one single pane of semi-transparent element (glass sheet) with the inclusion of an external solar protection device	N1	Opaque screen	4,21	0,07	1336,50	163,96	6,83
		N2	Venetian wood blind	4,21	0,14	1722,50	163,98	7,03
		N3	Metallic roller shutter	3,99	0,07	1174,50	163,40	6,88
		N4	Wood roller shutter	3,82	0,05	1062,50	162,95	6,86
		N5	Plastic roller shutter	3,72	0,07	1076,50	162,69	6,94
		N6	Plastic cover	3,72	0,04	3162,50	162,69	6,85
		N7	Metallic cover	3,99	0,04	1362,50	163,40	6,79
		N8	Wood cover	3,82	0,04	3262,50	162,95	6,83
Single glass window + Internal Solar Protection	Windows composed by one single pane of semi-transparent element (glass sheet) with the inclusion of an internal solar protection device	N1	Opaque curtain	4,21	0,34	1336,50	163,96	7,64
		N2	Roller blind	4,21	0,47	1722,50	163,95	8,06
		N3	Metallic shade	3,99	0,36	1174,50	163,4	7,76
		N4	Wood shade	3,82	0,36	1062,50	162,95	7,81
		N5	Plastic shade	3,72	0,36	1076,50	162,69	7,83
		N6	Plastic cover	3,72	0,31	3162,50	162,69	7,68
		N7	Metallic cover	3,99	0,31	1362,50	163,4	7,61
		N8	Wood cover	3,82	0,31	3262,50	162,95	7,65
Single glass window + Horizontal shading element	Windows composed by one single pane of semi-transparent element (glass sheet) with the inclusion of a horizontal shading element	N1	Overhang at 30° angle	-	-	140	173,68	6,72
		N2	Overhang at 45° angle	-	-	240	176,14	6,47
		N3	Overhang at 60° angle	-	-	420	178,79	6,33

Table 37 – Summary table of the energy balance for each integrated passive solution – external envelope

System	Description of the solution	Level of quality	Insulation layer thickness (mm)	Cost of investment (€)	N_{ic} (kWh/m²)	N_{vc} (kWh/m²)
External walls (U_{REF} = 0,50)						
-	-	N0	0	3500	165,8	8,64
ETICS	Perforated ceramic brick wall (150 mm) with insulation layer fixed to the outside surface	N1	50	5040	101,63	7,43
		N2	80	5460	95,76	7,36
		N3	100	5880	92,24	7,32
		N4	120	6300	89,85	7,29
Internal insulation	Perforated ceramic brick wall (150 mm) with insulation layer fixed to the inside surface	N1	50	5180	102,36	12,53
		N2	80	6020	96,59	12,3
		N3	100	6580	93,12	12,16
		N4	120	7140	90,78	12,07
Double wall	Double pane of perforated ceramic brick wall (110 - 150 mm) with insulation layer partially filling the air gap	N1	40	7700	102,18	4,78[1] 7,37[3]
		N2	60	7980	96,16	5,28[1] 7,31[3]
		N3	80	8400	92,44	5,62[1] 7,29[3]
		N4	100	8680	90,07	5,84[1] 7,26[3]
Double wall	Double pane of perforated ceramic brick wall (110 - 150 mm) with insulation layer filling the air gap	N1	40	7700	102,13	7,37
		N2	60	7980	96,11	7,31
		N3	100	8680	92,92	7,23
		N4	120	9100	90,32	7,23
Ventilated façade	Perforated ceramic brick wall (150 mm) with ventilated air gap and insulation layer fixed to the outside surface	N1	50	8400	101,25[1] 102,16[2]	4,86[1] 4,79[2]
		N2	80	9240	95,61[1] 96,3[2]	5,32[1] 5,27[2]
		N3	100	9800	92,23[1] 92,77[2]	5,63[1] 5,58[2]
		N4	120	10500	89,48[1] 90,39[2]	5,90[1] 5,81[2]
Roof (U_{REF} = 0,40)						
-	**-**	**N0**	**0**	**8500**	**165,8**	**8,64**
Inverted roof	Flat roof with installation of the thermal insulation layer above the waterproofing/vapour control layer	N1	60	11500	123,11	6,63
		N2	90	12000	119,56	6,42
		N3	120	12500	117,43	6,26
		N4	150	13000	116,01	6,16
Pitched roof, "cold loft"	Installation of thermal insulation layer on top of ceiling slab on lofted area	N1	80	15500	117,43	6,92
		N2	110	16000	115,29	6,62
		N3	140	16500	114,02	6,40
		N4	170	17000	113,16	6,32
Pitched roof, "warm loft"	Installation of thermal insulation materials between and/or laid over the structural system (rafter) of a pitched roof	N1	75	17500	123,11	4,62
		N2	110	18000	119,56	4,85
		N3	140	18500	117,43	4,99
		N4	170	19000	116,01	5,10
Glazed areas (U_{REF} = 2,80)						
-	-	N0	g = 0,88	362,5	165,8	8,64
Double pane window	Window composed by two panes of semi-transparent elements (glass sheets) with a spaced gap in between and limited by a frame	N1	g = 0,75	586	164,02	8,01
		N2	g = 0,75	1275	162,17	8,20
		N3	g = 0,40	1171	171,25	6,22
		N4	g = 0,40	1178	170,46	6,28
Note: 1 – weakly ventilated air gap; 2 – strongly ventilated air gap; 3 – non-ventilated air gap						

Concerning the ventilation systems, the ITECONS spreadsheet features an option for the automatic design of air openings on the buildings fabric once every other aspect is already defined in the software. These devices are designed in order to achieve the end result of 0,50 renovations per hour in the heating season, minimising heat losses due to air renovation, and 0,60 renovations per hour in the cooling season. As this solution does not bring any changes to the global energy balance returned by the software, it will not be object of a detailed economic study. The same conclusion applies to other natural ventilation solutions like the air duct system or the combined system of air ducts and autoregulated air inlets. Although these bring a significant improvement to the air flow rate of the habitable space, as presented in **Table 38**, these do not result on a significant contribution to energy saving.

Table 38 – Summary table of the integration of natural ventilation solutions to the base model building

Solution	Designation	Estimated Rph (h^{-1})	Nominal Rph (h^{-1})	n50	Air Flow rate (m^3/h)
N0	No ventilation devices	0,19	-	1,8	64,76
N1	Fixed Air inlet	0,5	0,31	1,8	171,75
N1	Auto Air inlet 2 Pa	0,5	0,32	1,8	175,66
N2	Auto Air inlet 10 Pa	0,5	0,31	1,8	173,88
N3	Auto Air inlet 20 Pa	0,5	0,32	1,8	176,51
N4	Air duct system (low ΔP)	0,54	0,36	1,8	188,89

Now for the active solutions, the biomass boiler and the photovoltaic (PV) panel, a different process was adopted. On the case of the biomass boiler, the chosen configuration related to the standard practice of the consumer market, as the best choice for residential building are typically the configurations with lower heating capacity which still are more than enough for the household panorama. Therefore, the adopted solution is presented in **Table 39**.

Table 39 – Adopted configuration for the biomass boiler

Solution	Nominal heating capacity [kW]	Conversion efficiency [%]	Cost of investment [€]	Energy production cost [€/kW]	Total energy production [kWh/year]
Wood pellet boiler	4,7 to 12,2	92	4000	0,04	18021,60

In relation to the photovoltaic panel solution, a similar process to the biomass boiler was pursued. After selecting the type o PV cell and the corresponding module the next step is the determination of the number of modules needed to optimise the integration of this technology on top of the roof of the base model building. Considering that the main focus point of this dissertation stands on the construction of autonomous houses, the integration of an electrochemical energy storage unknit (lithium-ion battery) is mandatory, in order to fulfil the heating and cooling needs whenever the energy production from the PV panel system is not sufficient. However, the integration of such solution would bring a high level of complexity on the determination of the optimal configuration, due to the need for a broad and detailed study. Therefore, in this case, the determination of the number of modules is only based on the yearly output of the solution and the matching of the global energy necessities. This will result in a gross over-estimation of the number of modules. However, for the purpose of this dissertation, it will serve as a reasonable starting point on the feasibility of the integration of the PV technology on autonomous housing projects. (Note: in order to reduce the level of over-estimation, the determination of the number of PV modules is based on the fixation of the maximum output power characteristic of the PV module, which is considered to be at an optimal inclination of 15°)

Table 40 – Summary table for the integration study of PV panels on the roof of the base model building

Season	Production per m² of PV module [kWh/m²]	Number of PV modules	Area of module [m²]	% of roof area	Final Production [kWh]
Cooling	172,75	34	1,629	55	9567,93
Heating	148,07				8200,89
				Total	**17769,83**
Type of cell	**Module Efficiency**	**Dimension [mm]**	**Maximum output power (W_p) [kW]**	**Expected cost [€ per module]**	
Monocrystalline silicon	21,1%	1558 x 1046 x 46	335	619,33	

3.3.8. Estimated feasibility of the solutions

In order to determine the feasibility of each individual solution related to the assessed impact on the global energy balance when integrated to the base model building, the following methodology was applied to each system: determination of the cost of investment (C_0); determination of the exploration costs of the residential building with the incorporation of the respective solution (C_{exp}); determine the accumulated cost of the global costs (C_g) (investment plus exploration) throughout a 15-year period.

$$C_g = C_0 + C_{exp} \ [€] \qquad (17)$$

The cost of initial investment of each solution were based on the research of several similar solutions to the ones adopted in this dissertation on the market therefore, the practicality of these values must be taken into further careful consideration as they translate the average marketed cost for each solution.

However, in the pursuit of achieving the most realistic financial investment standpoint for each individual system, the accumulated global costs the exploration costs were determined through the application of equation (18), considering parameters like the inflation rate and interest rate. These parameters assure a more accurate report of the accumulated global costs of each individual solution in relation to the initial investment point. The interest rate (*j)* was defined as 5% and 3% for the inflation rate (*i*).

$$C_g = C_0 + \sum_{k=1}^{n} C_{exp,1st\ year} \times \frac{(1+i)^{k-1}}{(1+j)^k} \ [€] \qquad (18)$$

For the determination of the exploration costs, determine the annual electricity consumption and the respective cost, through the previously determined energy necessities, and assuming a global efficiency of 100% for heating and cooling equipment. The cost of electricity was taken from the DGEG study on the average electric energy cost on the Portuguese domestic sector from 1985 to 2020.

Finally, the determination of the return-on-investment (ROI) period, associated with the adoption of each solution, was defined through the comparation of the savings with the initial investment cost. The ROI period will, therefore, amount to the number of year necessary for the parcel of the accumulated savings to match the invested capital, which is as expressed in equation (19), where S_1 is the energy savings on the first year of investment, and *r* the number of years necessary to achieve the return on investment.

$$C_0 = \sum_{k=1}^{r} S_1 \frac{(1+i)^{k-1}}{(1+j)^k} \ [€] \qquad (19)$$

4 THE CATALOGUE

4.1. INTRODUCTION

In this chapter, the technical data sheets of each studied system will be presented according to the structure defined in chapter 3. These are organized by the following order:

- Passive solutions – External walls
- Passive solutions – Roof systems
- Passive solutions – Glazed areas
- Active Solutions – Solar technology and Biomass

Passive Solutions - External Walls

ETICS – *External Thermal Insulation Composite System*

Technical and Economic analysis

General description:

Application of thermal insulation layer on the outside surface of external walls.

Performance parameters:

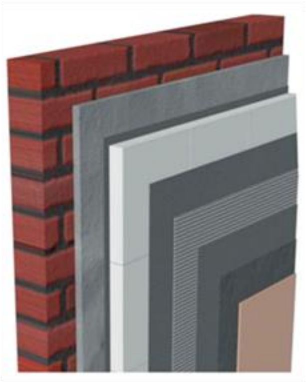
$\lambda_{insulation}$ = 0,037 (W/m.K)

U* = 0,25 – 0,5 (W.m^{-2}.ºC^{-1})

Solution's schematic:

There are two types of ETICS, bonded or mechanically fixed. The typical system components are, in application order:

- adhesive
- thermal insulation material
- anchors (if required)
- base coat
- reinforcement mesh (usually fibre glass)
- finishing layer (finishing coat with key coat and decorative coat)



General observations:

EPS, XPS, MW and ICB are the main materials for the thermal insulation layer

Economic assessment *

Estimated Investment Cost (€/m²)	Estimated Annual Energy Savings (€)	Return on Investment Period (years)
35 – 45	635 – 765	4

* These values are result from the economic assessment methodology developed in Chapter 3 page 42 and for the specific context of this work.

Recommendations:

- Application of systems with European Technical Approval – E.T.A
- Qualified professional installation
- Application of anti-biological proliferation treatment

Advantages:

- Strong thermal mass
- Minimal thermal bridging

Disadvantages:

- Conflicts with the building's façade design
- Reduced shock resistance
- Risk for growth of biological colonies

Passive Solutions - External Walls

Internal Insulation

Technical and Economic analysis

General description:

Installation of an insulation layer on the internal side of external walls

Performance parameters:

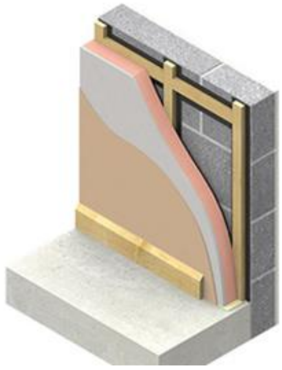
$\lambda_{insulation}$ = 0,037 (W/m.K)

U* = 0,25 – 0,5 (W.m^{-2}.ºC^{-1})

Solution's schematic:

This system is composed by the following components:

- Structural element
- Base coat
- Thermal Insulation
- Finishing layer (for example plasterboard and wood agglomerates)



General observations:

Internal Insulation systems are divided into two categories regarding the integration of the thermal insulation layer: need for the integration of a supporting structure (metallic or wood), or an adhesive preassembled component (insulated plasterboards)

Economic assessment *

Estimated Investment Cost (€/m²)	Estimated Annual Energy Savings (€)	Return on Investment Period (years)
37 – 51	575 – 705	5

* These values are result from the economic assessment methodology developed in Chapter 3 page 42 and for the specific context of this work.

Recommendations:

- Assessment of the intersection with the ceiling, skirting boards, glazed areas, and electrical installations
- Installation of a heavy finishing layer, for example brick masonry or concrete panels, which provide an increment to the thermal inertia of the envelope, consequently increasing the potential for passive gains of heat indoors

Advantages:

- No need for alterations to the architectural design of the façade
- Compatibility with services installations

Disadvantages:

- Persistency of thermal bridges and potential for hygrothermal issues
- Weakens the contribution of the thermal mass of external walls
- Reduction of usable implanted area

Passive Solutions - External Walls

Double walls façades

Technical and Economic analysis

General description:

Double pane wall with thermal insulation in-between

Performance parameters:

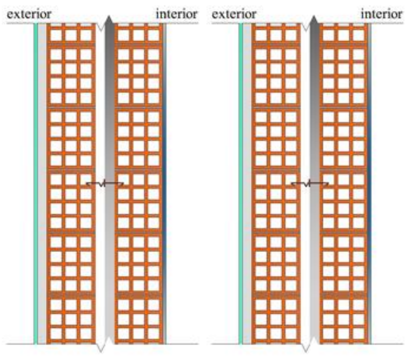
$\lambda_{insulation}$ = 0,037 (W/m.K)

U* = 0,25 – 0,5 (W.m^{-2}.ºC^{-1})

Solution's schematic:

This system is composed by the following components:

- Structural elements, inner and outer layer, either masonry wall or by a combination of concrete wall and masonry wall
- Exterior and interior finishing layers
- Thermal insulation completely or partially filling the gap between both structural layers
- Connecting stirrup



General observations:

Commonly used insulation materials are EPS, XPS, MW, ICB and polyurethane (PUR)

Insulation should be mechanically fixed to the inner layer and the correspondent air gap should not be under 30 mm (preferably 50 mm)

Economic assessment *

Estimated Investment Cost (€/m²)	Estimated Annual Energy Savings (€)	Return on Investment Period (years)
55 – 62	1- 630 – 775 2- 630 – 760	1- 7 2- 8

* These values are result from the economic assessment methodology developed in Chapter 3 page 42 and for the specific context of this work.

Recommendations:

- Heavier inner layers will increase the potential for passive heating indoors
- Elimination of thermal bridges along the interception of other construction elements like beams, columns and shutter boxes is necessary in order to achieve the best global performance

Advantages:

- Good potential for the use of the envelope's thermal mass
- Traditional construction solution

Disadvantages:

- Persistency of thermal bridges and potential for hygrothermal issues

Passive Solutions - External Walls

Ventilated façades

Technical and Economic analysis

General description:

Installation of an insulation layer on the external surface and a layer of air between the insulation material and the discontinuous external finishing layer

Performance parameters:

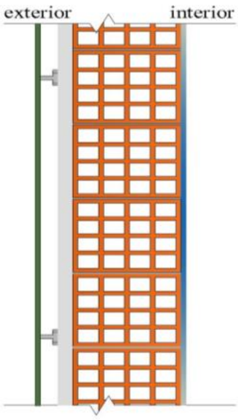
$\lambda_{insulation}$ = 0,037 (W/m.K)

U* = 0,25 – 0,5 ($W.m^{-2}.{}^{o}C^{-1}$)

Solution's schematic:

This system is composed by the following components:

- Structural element
- Waterproofing membrane
- Thermal Insulation
- Mechanical fixing and/or supporting structure
- Ventilated air space
- External discontinuous cladding



General observations:

This system can only be classified as ventilated if the distance between the cladding elements and the insulation layer is at least 20 mm, and as long as the eventual local reductions of air space (between 5 and 10 mm) do not compromise the draining and ventilation function

Economic assessment *

Estimated Investment Cost (€/m²)	Estimated Annual Energy Savings (€)	Return on Investment Period (years)
60 – 75	660 – 780	9

* These values are result from the economic assessment methodology developed in Chapter 3 page 42 and for the specific context of this work.

Recommendations:

- Air space cross-section must be over 50 cm^2 per linear meter
- Ventilation openings must, at least, be envisioned at the building base point and at the roof edge
- The external cladding must be sectioned for fire safety and wind pressure purposes
- Application of systems with European Technical Approval – E.T.A and qualified professional installation

Advantages:

- Strong thermal mass
- Minimal thermal bridging
- Reduction of condensations
- Great variety of external cladding options with great shock resistance

Disadvantages:

- Elevated investment and maintenance cost
- Potential for architectural incompatibilities

Passive Solutions – Roof systems

Inverted Flat Roof

Technical and Economic analysis

General description:

Flat roof with installation of the thermal insulation layer above the waterproofing/vapour control layer

Performance parameters:

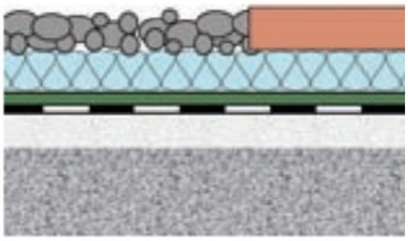
$\lambda_{insulation}$ = 0,037 (W/m.K)

U* = 0,2 – 0,4 (W.m^{-2}.ºC^{-1})

System's schematic:

Typically composed by:

- Upper protection layer
- Geotextile
- Thermal insulation layer
- Combined waterproofing/vapour control layer
- Shape layer
- Support structure



General observations:

The upper protection layer, typically ballast, prevents the lifting of the insulation. Also, the insulation layer effectively protects the waterproofing/vapour control membrane from thermal stress, UV light and mechanical damage

Economic assessment *

Estimated Investment Cost (€/m²)	Estimated Annual Energy Savings (€)	Return on Investment Period (years)
115 – 130	415 – 495	9

* These values are result from the economic assessment methodology developed in Chapter 3 page 42 and for the specific context of this work.

Recommendations:

- Ensure a continuous installation of the thermal insulation layer
- Accessible roof area

Advantages:

- Strong thermal mass
- Greater durability due to protection of the waterproofing/vapour control membrane

Disadvantages:

- Reduction of the thermal performance of the insulation layer due to exposure to moisture
- Maintenance for upper protection

Passive Solutions – Roof systems

Pitched roof, insulation at the rafter level (warm loft)

Technical and Economic analysis

General description:

Installation of thermal insulation materials between and/or laid over the structural system (rafter) of a pitched roof

Performance parameters:

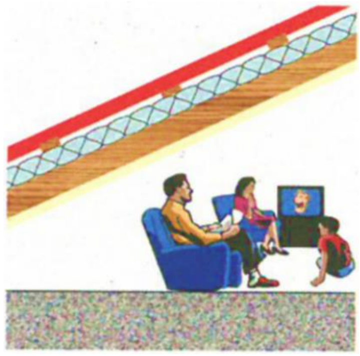
$\lambda_{insulation}$ = 0,037 (W/m.K)

U* = 0,2 – 0,4 (W.m^{-2}.ºC^{-1})

System's schematic:

Typically composed by:

- External cladding (ceramic tiles and composite boards)
- Ventilated air gap
- Waterproofing and vapour control membrane
- Thermal Insulation
- Wood rafters
- Finishing layer



General observations:

This insulation method creates a lofted area, which increases habitable space in a house. The insulation layer is fixed either between, above, or under the rafters in numerous combinations. Type of insulation: insulation boards and roll insulation. A ventilated air gap between the insulation and the external cladding is created through a batten and counter batten design.

Economic assessment *

Estimated Investment Cost (€/m²)	Estimated Annual Energy Savings (€)	Return on Investment Period (years)
175 – 190	435 – 505	> 15

* These values are result from the economic assessment methodology developed in Chapter 3 page 42 and for the specific context of this work.

Recommendations:

- Installation of a continuous insulation layer over the rafters will eliminate cold bridging in these elements
- Attention to vapour diffusion and airtightness details

Advantages:

- The insulation layer is protected
- The lofted area is passively heated by the heat flux of the rooms bellow

Disadvantages:

- This solution does not contribute to the thermal mass of the building

Passive Solutions – Roof systems

Pitched roof, insulation at the ceiling level (cold loft)

Technical and Economic analysis

General description:

Installation of thermal insulation layer on top of ceiling slab on lofted area

Performance parameters:

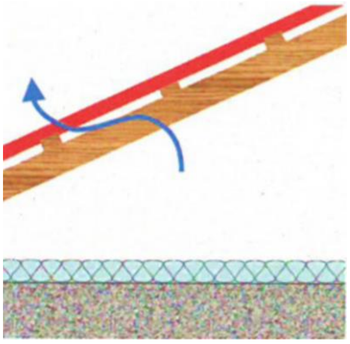
$\lambda_{insulation}$ = 0,037 (W/m.K)

U* = 0,2 – 0,4 (W.m^{-2}.ºC^{-1})

System's schematic:

Typically composed by:

- Ventilated lofted area
- Waterproofing and vapour control membrane
- Thermal Insulation
- Structural element (concrete slab)
- Finishing layer



General observations:

Installation of insulation layer on top of the ceiling slab reduces heat losses on the habitable space, bellow the lofted area. There is a high condensation risk when ceiling is very permeable to vapour, therefore, the lofted area must be strongly ventilated, or the roofing structure presents a certain permeability.

Economic assessment *

Estimated Investment Cost (€/m²)	Estimated Annual Energy Savings (€)	Return on Investment Period (years)
155 – 170	470 – 525	> 15

* These values are result from the economic assessment methodology developed in Chapter 3 page 42 and for the specific context of this work.

Recommendations:

- Installation of a second layer of insulation at 90 degrees to the first layer to reduce thermal bridging
- To ensure continuity of insulation, insulation must be applied to access elements like loft hatches
- Use raised legs structures for boarding systems when using loft as storage area

Advantages:

- Optimization of the thermal mass contribution
- Cheaper installation cost

Disadvantages:

- Loft is an unhabitable area
- Condensation risk

Passive Solutions – Glazed Area

Double Glazed Windows

Technical and Economic analysis

General description:

Window composed by two panes of semi-transparent elements (glass sheets) with a spaced gap in between and limited by a frame

Performance parameters:

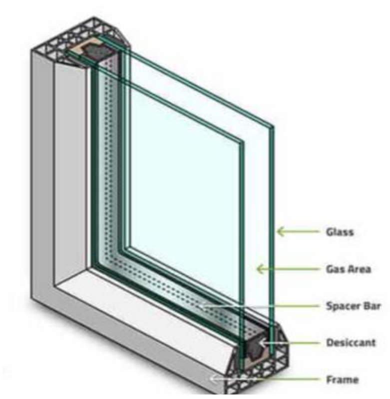
g^* = 0,75

U* = 1,4 – 2,8 ($W.m^{-2}.^{o}C^{-1}$)

System's schematic:

Typically composed by:

- Two panes of glass sheets (4 – 12 mm thickness)
- Spaced gap (6 – 20 mm width)
- Frame (wood, aluminium, PVC, etc.)



General observations:

Low ε glass and spacing chamber filled with air or mixture of gases (Argon, Krypton, Xenon), conferring a stronger barrier to heat flux through the glazed area and effectively reducing the solution's emissivity

Economic assessment *

Estimated Investment Cost (€/unit)	Estimated Annual Energy Savings (€)	Return on Investment Period (years)
330 – 590	25 – 45	> 15

* These values are result from the economic assessment methodology developed in Chapter 3 page 42 and for the specific context of this work.

Recommendations:

- Installation of special glass sheets with solar control treatment for reduced solar factor
- Adoption of aluminium frames only when thermal breaking is ensured

Advantages:

- Lower condensation risk on internal surface (in relation to single glass window)
- Greater thermal resistance
- Good levels of acoustic insulation

Disadvantages:

- Thicker system therefore higher complexity of installation
- Expensive installation

Passive Solutions – Glazed Area

Single Glazed Windows + External solar protection

Technical and Economic analysis

General description:

Windows composed by one single pane of semi-transparent element (glass sheet) with the inclusion of an external solar protection device

Performance parameters:

$g_{\perp,vi}$ = 0,88
g_{tot} = 0,04 – 0,14
U_{wdn} = 3,82 – 4,21 (W.m^{-2}.ºC^{-1})

System's schematic:

Typically composed by:

- Single pane of glass sheets (4 – 12 mm thickness)
- Frame (wood, aluminium, PVC, etc.)
- External Solar Protection

General observations:

Integration of traditional shutters, roller shutters, blinds, and covers, of different materials (wood, plastic, and metal) into a single glazed window.

Economic assessment *

Estimated Investment Cost (€/unit)	Estimated Annual Energy Savings (€)	Return on Investment Period (years)
530 - 1635	35 – 55	> 15

* These values are result from the economic assessment methodology developed in Chapter 3 page 42 and for the specific context of this work.

Recommendations:

- Installation of shading device with adjustable levels of shading

Advantages:

- Confers performance versatility to the window
- Significant reduction of heat gains due to solar radiation
- Keeps radiation outside of the building

Disadvantages:

- Reduced durability of the protection devices
- Higher maintenance costs than internal shading devices

Passive Solutions – Glazed Area

Single Glazed Windows + Internal solar protection

Technical and Economic analysis

General description:

Windows composed by one single pane of semi-transparent element (glass sheet) with the inclusion of an internal solar protection device

Performance parameters:

$g_{\perp,vi}$ = 0,88

g_{tot} = 0,31 – 0,47

U_{wdn} = 3,82 – 4,21 ($W.m^{-2}.^{o}C^{-1}$)

System's schematic:

Typically composed by:

- Single pane of glass sheets (4 – 12 mm thickness)
- Frame (wood, aluminium, PVC, etc.)
- Internal Solar Protection

General observations:

Integration of traditional blinds, shades, curtains and covers, of different materials (wood, plastic, and metal) into a single glazed window.

Economic assessment *

Estimated Investment Cost (€/unit)	Estimated Annual Energy Savings (€)	Return on Investment Period (years)
530 - 1635	25 – 45	> 15

* These values are result from the economic assessment methodology developed in Chapter 3 page 42 and for the specific context of this work.

Recommendations:

- Installation of shading device with adjustable levels of shading

Advantages:

- Confers performance versatility to the window
- Significant reduction of heat gains due to solar radiation
- Low-cost maintenance and high durability of the shading elements

Disadvantages:

- Cannot maintain solar radiation outside of the building promoting the of "hot air pockets" between shading element and the window

Passive Solutions – Glazed Area

Single Glazed Windows + Horizontal shading element

Technical and Economic analysis

General description:

Windows composed by one single pane of semi-transparent element (glass sheet) with the inclusion of a horizontal shading element

Performance parameters:

$g_{\perp,vi}$ = 0,88

g_{tot} = 0,46 – 0,55

U_{wdn} = 4,9 (W.m^{-2}.ºC^{-1})

System's schematic:

Typically composed by:

- Single pane of glass sheets (4 – 12 mm thickness)
- Frame (wood, aluminium, PVC, etc.)
- Concrete overhang

General observations:

Integration of concrete overhang on top of a single glazed window. Theoretical line connecting overhang extremity and the middle section of the window at 30°, 45° or 60° in relation to the parallel line to the glazed area.

Economic assessment *

Estimated Investment Cost (€/unit)	Estimated Annual Energy Savings (€)	Return on Investment Period (years)
70 – 210	Not viable	Not viable

* These values are result from the economic assessment methodology developed in Chapter 3 page 42 and for the specific context of this work.

Recommendations:

- Installation of the overhang on façades oriented to the south is the optimal configuration for this solution

Advantages:

- High durability solution
- Low maintenance requirements
- Blocks unwanted solar radiation during the summer and allows solar radiation heat gains during the winter

Disadvantages:

- Low versatility solution

Active Solutions

Biomass Boiler

Technical and Economic analysis

General description:

Boiler fuelled by wood pellets

Performance parameters:

Nominal heating capacity: 4,7 to 12,2 kW

System Efficiency: 92%

System's schematic:

- Combustion chamber
- Flue
- Smoke extracting system
- Heat exchanger unit
- Ash plate
- Combustion control system with integrated probe
- Fuel deposit unit (hopper)

General observations:

A domestic scale biomass boiler is around 1,0 m³ of volume.

Variable system configurations depending on feeding and cleaning processes: manual or automatic.

Economic assessment *

Estimated Investment Cost (€)	Estimated Annual Energy Production (kWh)	Annual Operation Cost (€)
4 000	18 000	600 – 1000 (About 50% of original electricity costs)

* These values are result from the economic assessment methodology developed in Chapter 3 page 42 and for the specific context of this work.

Recommendations:

- Professional installation
- Detailed feasibility study before investment
- Ensure a well-insulated building fabric for the best efficiency system

Advantages:

- Versatile fuel range
- Stable fuel prices
- Cleaner energy source (low CO_2 emissions)
- Integration to both central heating and DHW systems

Disadvantages:

- Very high capital cost
- Fuel storage can take a lot of space
- Fuel costs are variable – dependent on source, distance from supplier and quantity
- High cleaning and maintenance requirements

Active Solutions

Photovoltaic Panel + storage system

Technical and Economic analysis

General description:

Installation of photovoltaic panels on the rooftop of a house for generation of electric energy

Performance parameters:

Maximum power rating: 335 kW
System Efficiency: 21,1%

System's schematic:

- Photovoltaic modules
- Inverter
- Lithium-ion Battery

General observations:

Type of PV cell: Monocrystalline silicon; Module dimension: 1558 x 1046 x 46 mm
Battery useful capacity: 6,4 kWh; Battery power: 3,3 kW
Round-trip efficiency: 92,5%

Economic assessment *

Estimated Investment Cost (€)	Estimated Annual Energy Production (kWh)	Estimated annual savings (€)
21 000 (+ 3000 for battery)	17 800	1800 – 1900 (Covering 100% of heating and cooling necessities)

* These values are result from the economic assessment methodology developed in Chapter 3 page 42 and for the specific context of this work.

Recommendations:

- Professional installation
- Detailed feasibility study and assessment of potential for a phased investment
- Ensure a well-insulated building fabric for the best efficiency system
- Optimal inclination of photovoltaic modules around 10° to 15°

Advantages:

- Most reliable energy production technology for autonomous houses
- Clean energy source
- Potential for a profitable solution by selling produced electricity

Disadvantages:

- Very high capital cost
- Unstable production

5 CONCLUSION

5.1. MAIN CONCLUSIONS

The present dissertation provides support for developers, project managers and owners to better assess what active and passive solutions will better suit their needs for the construction of residential buildings, with increased focus on thermal autonomous housing. The development of a building project is typically very time consuming, mainly due to the need for extensive research on the compatible solutions. Often times, this results in a minimal efforted attempt and simpler adoption of the more traditional systems. On the other hand, with incentive on the gathering of technical and economic data of several systems, the potential for the diffusion of alternative solutions, that might be more appropriate to the project in hand, would be increased, also contributing to the certification and amplified guarantees of these elements.

The assessment of the efficiency of the gathered solutions in this catalogue was mainly based on the Portuguese energy certification system and through the aid of the available spreadsheet developed by ITECONS, which automatizes the calculation of the several components envisioned on the regulation practise. The adopted methodology supplied the expected impact of the solutions on the energy balance of a hypothetical residential building. This study case was considered as representative of a bellow average solution in terms of energy efficiency, in order to display the impact of the tested systems more intensively. For example, the energy balance of this building, as expected, resulted on an extreme underperformance, outcoming the reference value by 314,8% in the calculated heat losses through transmission in the heating season. Therefore, the integration of solutions with thermal insulation on the external envelope have very high potential for a substantial positive impact on the annual useful energy heating needs. This chain of thought was pursued on the remaining solutions, and it was organized in the technical data sheets that compose this catalogue in an easy interpretation form.

In the end, the economic saving is more often the driver for investing in active and passive solutions. Hence, it is recommended that a focus is given to this aspect, to increase homeowner's intentions towards these solutions. However, the increase on the quality of life that these solutions can contribute to, should not be forgotten nor unappreciated. Hence, there should be considered a balance between these aspects.

The end result of this thesis contributes to the existing knowledge around thermal autonomous households and enlightens a simplified analysis of the different solutions currently available. The different aspects to be considering when choosing to invest in an active or passive solution are presented. A comparison based on energy saving and return on investment is provided and assorted to the respective technical data sheet. Understanding the outcomes of each solution is crucial for an informed decision making since owners have limited investment capability.

5.2. LIMITATIONS AND FUTURE RESEARCH

Even though the present thesis adds a simplified vision to the approach of active and passive solutions for thermal autonomous housing, it is important to point out its limitations and unexplored paths that can be improved and opportune to investigate in future research.

First, given this study was developed for a hypothetic case study based on the North region of Portugal, the results of the assessment done are limited to this region context. Therefore, it would be interesting to explore the same active and passive solutions for thermal autonomous housing solutions in different climate regions or countries to understand the differences and possible relationships with the present findings.

Second, this thesis focuses on the assessment of the general system and does not go in depth in each of the solutions. Future research could complete this catalogue by investigating in depth each of the solutions in different environments.

Third, the construction of thermal autonomous housing is gaining prominence in recent years hence, the catalogue is and will continue to be in constant update as technology evolves and new solutions might appear. Thus, the current catalogue should be seen as a basis for future work that continues to update the information on this topic.

Fourth, the base model used to analyse the energy savings and the return-on-investment period for each system was very general and even over simplified and does not consider all the variables that developers, project managers and owners might encounter in the specific household context. Hence, a more detailed and dynamic study for each solution, involving the adaptive thermal comfort concept, with the aid of more complex software, might provide for more accurate and specific information to improve the catalogue.

Finally, when researching on the theme of autonomous houses, the modular house concept demonstrated a very high potential for compatibility with the first subject, and also the approach to the ever-rising topic of sustainability and environmental consciousness of the construction sector, will make this concept a very interesting subject for further investigation and deliberation.

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