Unveiling the social costs of fuel poverty in Lisbon public housing

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To the many with whom I shared time and passion.

Abstract

This study assesses the viability of public housing retrofitting taking into account the social costs derived by fuel poverty, a situation of vulnerability driven by a combination of low income and poor living conditions regarding energy consumption and thermal comfort. Enhanced comfort conditions have positive effects on individuals' health and social life, which translates into economic relief for the National Healthcare Service (NHS). This dimension is too often neglected when determining the economic feasibility of building retrofits, which may lead to the exclusion of vulnerable groups from subsidy schemes and further degradation of the typically aged and inefficient public housing stock. Indeed, the renovation of low-income housing may result unprofitable under conventional methods due to multiple factors, such as the low price of energy due to subsidized utility tariffs, the below-average energy consumption of residents and their inability to take charge of the investment. An adaptation of the Index of Vulnerable Homes (IVH) was used to quantify individuals' NHS expenses according to their net income, energy expenses and thermal comfort. The Quality-Adjusted Life Years (QALY) and Health-Related Quality of Life Cost (HRQLC) required by the IVH methodology were calculated from a Portuguese EQ-5D-5L value set. City Energy Analyst, a Urban Building Energy Modelling (UBEM) software, was used to simulate the energy demand and thermal comfort of around 1,700 buildings in eight social neighbourhoods in Lisbon. Three retrofit passive scenarios were studied. The results of this study offer local authorities further clarity when it comes to understanding the impact of building retrofit on fuel poverty, prioritizing the renovations of the public housing stock and adequately allocating public funding.

Keywords: Thermal comfort; **Fuel poverty**; UBEM; **Dynamic building simulation**; Building retrofit; QALY; HRQLC; **Public housing**

Resumo

Esta tese analisa a reabilitação do parque edificado de bairros sociais afetados pela problemática da pobreza energética, nomeadamente baixos rendimentos, condições precárias da habitação e desconforto térmico.

A melhoria das condições de conforto térmico na habitação tem efeitos positivos na saúde e na vida social dos indivíduos, traduzindo-se em redução de despesas para o Serviço Nacional de Saúde (NHS).

Esta dimensão é frequentemente negligenciada na análise da reabilitação de edifícios, o que pode levar à exclusão de grupos vulneráveis e degradação adicional do parque edificado de habitação pública tipicamente envelhecido e ineficiente. A renovação de habitações de renda reduzida pode revelar-se não lucrativa considerando métodos de análise de investimento convencionais devido a fatores como o baixo preço da energia (rendas subsidiadas), consumo de energia abaixo da média nacional e incapacidade dos ocupantes assumirem o controlo do investimento. Para analisar de forma holística o processo de reabilitação, foi considerada a adaptação do Índice de Casas Vulneráveis (IVH), quantificando as despesas previstas do NHS com os ocupantes dos edifícios de acordo com o seu rendimento, despesas com energia na habitação e conforto térmico. Os anos de vida ajustados pela qualidade (QALY) e o custo da qualidade de vida relacionado com a saúde (*HRQLC*) exigidos pela metodologia IVH foram calculados a partir de um conjunto de valores EQ-5D-5L português. O City Energy Analyst, um software de modelação energética urbana de edifícios, foi utilizado para simular o consumo energético e o conforto térmico de cerca de 1700 edifícios em oito bairros sociais de Lisboa. Três cenários passivos de retrofit foram estudados. Os resultados deste estudo providenciam às autoridades locais mais clareza no impacto sobre a pobreza energética decorrentes da reabilitação de edifícios, permitindo definir prioridades na reabilitação do parque habitacional público e alocar adequadamente financiamento.

Palavras-chave: Conforto térmico, **Pobreza Energética**; **Simulação dinâmica de edifícios**; Reabilitação de edifícios; **Habitação social**

Acknowledgments

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The author acknowledges Gebalis for the data provided.

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List of abbreviations and acronyms

Abbreviation	**Explanation**
a	Appliances category
A	Number of adults per family unit
A_{dw}	Average dwelling size (in square meters)
AEC	Average per capita domestic Electricity Consumption (in kilowatt hour)
ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers
avg	Average
B	Number of minors per family unit
b_{neigh}	Share of minors living in each neighbourhood
BIP/ZIP	*Bairros e Zonas de Intervenção Prioritária de Lisboa* Lisbon's Neighbourhoods and Zones of Priority of Intervention
BPIE	Buildings Performance Institute Europe
BU	Bottom-Up
CAT	Category
CEA	City Energy Analyst
CH	Switzerland
CI	Thermal Comfort Indicator
CO_2	Carbon dioxide
COVID-19	Coronavirus Disease 19
CML	*Câmara Municipal de Lisboa* - Lisbon City Hall
CR	Cost of Retrofit (in euros)
δ	Average number of people by conventional dwelling
DR	Discount Rate
DHW	Domestic Hot Water
E_h	Energy hourly load (in watt hour per square meter)
Ea_Wm2	Appliances peak load *(CEA nomenclature)*
EB	Example Building
EC	European Commission
ED	End-use Energy Demand (in kilowatt hour)
EE	Household Energy Expenditure
EED	Energy Efficiency Directive
EEFR	Energy Efficiency Façade Retrofitting
el	Electricity
EL	Electricity consumption (in kilowatt hour)
El_Wm2	Lighting peak load *(CEA nomenclature)*

Abbreviation	**Explanation**
ELPRE	*Estratégia de Longo Prazo para a Renovação de Edifícios* Portuguese Long-Term Building Renovation Strategy
EM	Engineering Method
EN	European Norm
EnI	Energy Indicator
EPBD	Energy Performance in Buildings Directive
EP	Energy Poverty
EPC	Energy Performance Certificate(s)
EPS	Expanded Polystyrene
EQ-5D-5L	Five-level European Quality of Life 5 Dimensions' questionnaire
EU	European Union
GDP	Gross Domestic Product
h_{use}	Hours of use per day
HE	Household Housing expenditure
HM	Hybrid Method
HRQLC	Health-Related Quality-Life Cost
HVAC	Heating, Ventilation and Air Conditioning
IAQ	Indoor Air Quality
IDEF	*Inquérito às Despesas das Famílias* - Survey on Household Expenditure
INE	*Instituto Nacional de Estatística* - National Institute of Statistics
IPCC	Intergovernmental Panel for Climate Change
IT	Italy
ITE	*Informação Técnica de Edifícios* - Technical Information of Buildings
IVH	Index of Vulnerable Homes
LCC	Life Cycle Cost
LNEC	*Laboratório Nacional de Engenharia Civil* - National Laboratory of Civil Engineering
Lx	Lisbon
MEC	Median Energy Consumption
MPI	Monetary Poverty Indicator
MPT	Monetary Poverty Threshold
N_{hh}	Number of households per building
NG	Natural Gas
NHS	National Health Service
NHS_cost	National expenditure on healthcare per capita
NPV	Net Present Value
nZEB	nearly Zero Energy Building

Abbreviation	Explanation
NI	Household Net Income
Occ_m2pax	Occupation density *(CEA nomenclature)*
p	Relative peak load (in watt per square meter)
P	Peak power (in watt)
pc	Per capita
pm2	Per square meter
PER	*Programa Especial de Realojamento* - Special Program for Relocation
PIMP	*Plano de Intervenção a Médio Prazo para a Habitação Social de Lisboa* Mid-Term Action Plan for Social Housing in Lisbon
pr_{use}	Probability of use at a certain hour
PT	Portugal
PUAL	*Plano de Urbanização do Alto do Lumiar* - Urbanization Plan of Alto do Lumiar
PVC	Polyvinyl chloride
Q1	First Income Quintile
Q1 Lx	First Income Quintile in Lisbon
QREN	*Quadro de Referência Estratégico Nacional* - National Strategic Reference Framework
Qs_Wpax	Peak sensible heat load of people *(CEA nomenclature)*
RB	Real Building
RCCTE	*Regulamento das Características de Comportamento Térmico dos Edifícios* Regulation on Characteristics of Thermal Performance of Buildings
ref	Reference
ROI	Return On Investment
SM	Statistical Method
SMPT	Severe Monetary Poverty Threshold
T	Threshold
TB	Theoretical Building
TD	Top-Down
UBEM	Urban Building Energy Modelling
Uc	Equivalent household size
Vw_lpdpax	Daily fresh water consumption *(CEA nomenclature)*
Vww_lpdpax	Daily domestic hot water consumption *(CEA nomenclature)*
X_ghpax	Moisture released by occupancy *(CEA nomenclature)*
XPS	Extruded Polystyrene
Y	Useful life years

List of units

Symbol	**Name**	**Quantity**
°C	Degree(s) Celsius	Temperature
€	Euro(s)	Currency
€/y	Euro(s) per year	Currency per unit of time
g/p·h	Gram(s) per person per hour	Mass per capita per unit of time
h	Hour(s)	Time
h/d	Hours per day	*Adimensional*
K	Degree Kelvin	Temperature
kWh	Kilowatt hour(s)	Energy
kWh/m^2	Kilowatt hour(s) per square meter	Energy per unit area
kWh/p·y	Kilowatt hour(s) per person per year	Energy per capita per unit of time
kWh/m^2·y	Kilowatt hour(s) per square meter per year	Energy per unit area per unit of time
l/(p·d)	Liter(s) per person per day	Volume per capita per unit of time
M	Millions	*Adimensional*
m^2	Square metre(s)	Area
m^2/dw.	Square meter per dwelling	Dwelling size
m^2/p	Square meter per person	Occupation density
Mtoe	Mega ton(s) of oil equivalent	Energy
p/dw.	Number of people per dwelling	Household size
W	Watt(s)	Power
W/K	Watt(s) per degree Kelvin	Thermal conductance
W/m^2	Watt(s) per square meter	Power per unit area
W/(m^2·K)	Watt(s) per square metre per degree Kelvin	Overall heat transfer coefficient
W/p	Watt(s) per person	Power per capita
Wh/m^2	Watt hour(s) per square meter	Energy per unit area
y	Year(s)	Time

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1. Introduction

According to the last assessment of the Energy Efficiency Directive (EED), European Member States are moving slightly above the fixed trajectory towards the 2020 target. Indeed, the energy consumption of the European residential sector rose by 7% between 2014 and 2017, undermining the positive results achieved since then (European Commission, 2019). In this context, there is a clear need to step up efforts on building retrofitting, not only to avoid falling short on the 2020 targets but also to set the right basis for the subsequent decade when an even higher level of ambition will be required.

Energy renovations would be particularly beneficial in Southern Europe, where around 65-75% of the housing stock ages back before the first regulations on energy performance on buildings were written (1976–1979) (Escandón et al., 2017). The buildings erected before those years (1990 for Portugal) do not incorporate any specific measures for thermal insulation in their envelopes and are therefore obsolete from an energetic point of view. Additional efforts to improve energy efficiency would also have complementary benefits, such as lower energy bills, better health (through improved air quality), higher comfort and less fuel poverty (European Commission, 2019). From a macroeconomics perspective, building renovations also encourage economic activity, job creation and improvements in households' standards in terms of finance and quality-of-life (Copenhagen Economics, 2012; Mikulić et al., 2016).

In fact, energy-inefficient buildings are one of the main drivers of fuel poverty, a condition affecting between 50 to 125 millions Europeans (Atanasiu et al., 2014). In some Southern European countries, mild winters typical of Mediterranean climate lead to a relevant share of households not using any type of heating system, 15% in the case of Lisbon. Unsurprisingly, this ratio rises to 35% for Lisbon's poorest income quintile (INE, 2019a), since monetary deprivation certainly intensifies the risk of fuel poverty mostly by affecting the housing quality (Seebauer et al., 2019). The only strategy available to these vulnerable residents is, then, to dress up and eventually stand the cold.

In conclusion, living in conditions of fuel poverty implies suffering thermal discomfort and poor levels of Indoor Air Quality (IAQ). As a consequence, the energy vulnerable population is more prone to suffering health conditions, both physical (cardiovascular and respiratory) and mental (depression and stress, especially in young people) (Santamouris et al., 2014) as well as social exclusion, poorer diets, more hospital admissions and development, educational and psychological problems in children (Barnett et al., 2005). These issues translate into a societal problem in terms of increased risk of poverty, increased expenses for the National Health Service (NHS) and the dissolution of social fabric.

Passive architectural interventions such as energy efficiency facade retrofitting (EEFR) have shown a strong potential to tackle fuel poverty (Camprubí et al., 2016; Peralta et al., 2017). Improving the thermal properties of the envelope, these interventions manage to decrease the winter thermal load required to maintain a comfortable temperature inside the house and to eliminate the moisture pockets causing the formation of mould or leakages. EEFR interventions have demonstrated to increase thermal comfort (Curado and de Freitas, 2019; Mancini et al., 2016; Monteiro et al., 2017) and to reduce cold-related morbidity and mortality rates (Peralta et al., 2017). In a Mediterranean climate, passive measures alone could lead to a substantial decrease in thermal dissatisfaction, in line with the margins of tolerance set by Europe (European Standards, 2012).

Various studies focusing on social housing in the Mediterranean climate have verified that passive measures alone can reduce the thermal load between 45% to 80% in winter (Serrano-Lanzarote et al., 2017; Suárez and Fernández-Agüera, 2011) and between 30% to 48% in summer (Monteiro et al., 2017; Suárez and Fernández-Agüera, 2011), resulting in a reduction in the annual energy demand between 36% to 63% (Mancini et al., 2016; Monteiro et al., 2017; Serrano-Lanzarote et al., 2017; Suárez and Fernández-Agüera, 2011). Considering energy savings to pay back the investment, those retrofits are characterized by payback times between 11 to 25 years (Mancini et al., 2016; Semprini et al., 2017).

Despite these results, investments in public building retrofits may encounter several economic barriers, such as the inability for low-income households to participate in the investment. An additional obstacle often encountered in research is the so-called ‘performance gap’, that is the difference between the energy performance improvement estimated through simulation and the real performance of a building after the retrofit measures are completed. For instance, national directives to calculate the energy demand are based on the assumptions that comfort level is maintained within tolerable boundaries, which is often not the case for low-income households that scarcely rely on a heating system and thus consume much less energy than the estimates (Monteiro et al., 2017). Energy efficiency policies are often motivated by CO_2 emissions reduction and energy savings, this may lead to designing policies that increase inequalities when they do not specifically target vulnerable groups or even target higher consumers, which usually belong to wealthier groups (Camprubí et al., 2016). All the above reduces the energy savings normally guaranteed by passive retrofitting, making the investments less effective due to excessive payback periods. Public health or fuel poverty are not always the primary concerns of energy efficiency retrofitting policies, so that the benefits in thermal comfort and health recovery are often neglected because of its non-monetary nature (Monteiro et al., 2017). This may result in exclusion of vulnerable groups (less affluent and fuel poors) from subsidy schemes (Camprubí et al., 2016a) and further degradation of the already inefficient public housing stock.

Precisely, some studies have proposed to translate non-monetary benefits of retrofitting into the calculations of the payback time (Semprini et al., 2017). Indeed, the improvement in IAQ would lead to better health conditions for the tenants, which would, in turn, reduce the pressure on the National Health Service (NHS) and the related public expenses. This kind of strategy requires intersectional policy efforts, analogous to the “Warmth and Wellbeing Scheme”, launched under the Irish Government's Strategy to Combat fuel poverty, in which free energy efficiency measures are delivered to people affected by a chronic respiratory disease (“Warmth and Wellbeing,” 2017).

Through their Index of Vulnerable Homes, Castaño-Rosa et al. (2020a) evaluate the amount of money saved by the NHS after the retrofit of a social housing block in Southern Spain, concluding that those savings could pay back the investment required for the case study in around 3 years (Castaño-Rosa et al., 2020a, 2020b). Since it relies on the collection of a considerable amount of data on the thermal properties of the buildings and the economic situation and the living conditions of their inhabitants, the application of this methodology is limited to a small sample of households and its scale-up may be demanding.

To provide local authorities with a scalable and relatively quick procedure, this study aims to extend the methodology of Castaño-Rosa et al. (2020a) to a considerably larger sample, represented by seven social neighbourhoods in Lisbon. The originality of this work consists in the application of Urban Building Energy Modelling (UBEM), a system which uses reference buildings (or archetypes) to characterize the energy performance of large samples of buildings, even entire neighbourhoods or cities, in a faster way (Reinhart and Davila, 2016).

In this context, the Portuguese long-term building renovation strategy (*ELPRE - Estratégia de Longo Prazo para a Renovação de Edifícios*), which passed public consultation in May 2020, elaborated 38 building archetypes to characterize the national housing stock and analyse the potential of passive retrofitting. Apart from the monetary savings coming with the enhanced energy efficiency, the study also estimated the economic benefits related to asset valorization, work productivity and residents' health. This last parameter was calibrated to one less medical examination per year, which accounts for 52€ saved per household (República Portuguesa, 2020).

This project uses just 5 archetypes, developed within the SusCity project, to represent the public housing stock of Lisbon. City Energy Analyst (CEA) was the software used to simulate the energy demand and thermal comfort of the case study, composed of seven social neighbourhoods. By sacrificing the individuality of each building, the study aims to provide a plausible analysis of different retrofit scenarios for an area of around 1,700 buildings hosting 22,000 people.

2. Literature review

2.1 Building efficiency and energy poverty

In Europe the residential sector alone accounts for 20-25% of final energy consumption, similarly in Portugal (IEA, 2019). Reduction in the energy demand and decarbonization of the sector are then crucial in order to meet the IPCC demand to maintain the increase in global temperature below 2°C (or better 1.5°C) (IPCC, 2018), as enshrined in the Paris Agreement (UNFCC, 2015).

In this context, the European Union has abundantly enacted, namely through:

- the Energy Performance in Buildings Directive (EPBD), introduced in 2007 to limit the overall energy demand of new buildings and updated in 2013 with tighter requirements, including on building renovations and specific components (European Union, 2010);
- the Energy Efficiency Directive (EED), setting the target of 20% reduction of each Member State's energy intensity by 2020 as compared to 2005 values (European Union, 2012) and bringing it up to 32.5% by 2030 (European Union, 2018);
- the Horizon 2020 funding programme for research (European Commission, 2020).

While the EPBD has demonstrated an excellent technical instrument for new buildings, the increasingly low share of renovations on the total construction permits has made those improvements futile. In Portugal, for example, the percentage of buildings concluded that was undergoing a renovation passed from 35% in 2013 to only 25% in 2018 (a value reducing to 20% for the Lisbon Metropolitan Area) (INE, 2019b). While recovering from the 2008 economic crisis, the total amount of construction works continued to soar, offsetting at least partly the benefits obtained with the EPBD.

In the last assessment of the progress made by Member States towards the national EED targets, the wealth effect (translated as a higher number of dwellings and a bigger average floor area) and lifestyle changes (such as increasing penetration of new small appliances) are depicted as some of the reasons why, after dropping by some 9% from 310 Mtoe in 2005 to 284 Mtoe in 2014, the energy consumption of the european residential sector rose by 7% between 2014 and 2017, moving slightly above the fixed trajectory towards the 2020 target (European Commission, 2019). Indeed, in Portugal the energy intensity of the residential sector reached a minimum value of around $70\ \frac{kWh}{m^2}$ in 2013, only to grow again from the year after. To be fair, the best other european countries have achieved is to stabilize the trend, even if at much higher values of $160-170\ \frac{kWh}{m^2}$ for Italy, Germany or Sweden (IEA, 2019).

Energy renovations would be particularly beneficial in Southern Europe, where around 63 and 76% of the total housing stock ages back before the first regulations on energy performance on buildings were written (1976–1979) (Escandón et al., 2017). According to the 2011 census, 65% of the residential housing stock in Portugal (69% in Lisbon) was built before 1990 (INE, 2020), when the first national energy efficiency regulation was introduced (Fragoso et al., 2018). Most of these residential buildings do not incorporate any specific measures for thermal insulation in their envelopes, and are therefore obsolete from an energetic point of view. Indeed, buildings constructed in Portugal in the 1980s present an average yearly energy demand of $95 \frac{kWh}{m^2}$ for heating versus the $38 \frac{kWh}{m^2}$ of post-2013 buildings; similarly the cooling demand passed from 16 to $10 \frac{kWh}{m^2}$ (Fragoso et al., 2018).

In this context, it has become clear that there is a need to step up efforts not only to reach the 2020 targets but also to set the right basis for the subsequent decade when an even higher level of ambition will be required. Additional efforts to improve energy efficiency would also have complementary benefits, such as lower energy bills, better health (through improved air quality), more comfort and less energy poverty (European Commission, 2019). From a macroeconomics perspective, building renovations also encourage economic activity, job creation and improvements in households' standards in terms of finance and quality-of-life (Copenhagen Economics, 2012; Mikulić et al., 2016).

In fact, energy inefficient buildings are one of the main drivers of energy poverty, a condition affecting between 50 to 125 millions europeans (Atanasiu et al., 2014). The high approximation of these numbers is given by the lack of a coherent definition that could steer the EU into a coordinated approach (European Union, 2009; Thomson et al., 2017). Efforts in that direction have generally revolved around the inability of households to satisfy their basic needs because of a lack of energy services or resources (Bouzarovski and Petrova, 2015; Horta et al., 2018).

First introduced by the seminal work of Boardman (1991), a common approach based on objective indicators considers that the condition of energy poverty (or fuel poverty) occurs when a household's annual energy expenditure exceeds 10% of its disposable income (Boardman, 1991; Thomson et al., 2017). The definition effectively portrays the situation in Northern European countries like Germany, UK or Sweden, where cold winters put inhabitants of inefficient buildings at immediate risk, forcing them to pump up their fuel expenses to avoid serious health issues. On the contrary, in some Southern European countries, mild winters typical of Mediterranean climate lead to a relevant share of households still using wood fuels (30% in Portugal) (EU Energy Poverty Observatory, 2019), that are not accounted into energy bills, or having no heating system at all (11% in Portugal, 15% in Lisbon) (INE, 2020). More than by choice, these figures surge from the consistent portion (73% in 2005) of low income portuguese households unable to afford the expenses for heating (Santamouris et al., 2014).

The only strategy remaining to these vulnerable residents is, then, to dress up and eventually stand the cold. As a matter of fact, all the three case studies analysed by Escandon et al. (2017) in Andalucia (Southern Spain) revealed average indoor temperatures measured between 13°C and 18.8°C (below the 18-20°C comfort threshold used by EN15251) (European Standards, 2012) in the harshest winter month (January), with tenants experiencing discomfort between 92.9% to 100% of the time (Escandón et al., 2017; European Standards, 2012).

In that direction, Santamouris et al. (2014) measured the indoor temperatures of 43 low-income dwellings in Athens in January, finding average values ranging from 11.4°C to 19.6°C, while the corresponding minimum varying between 5°C and 16.2°C. The majority of the households were in condition of partial deprivation, experiencing discomfort for more than 60% of the time (still 30% for the best performing group), with one-third living under high or very high deprivation with discomfort time up to 100% for the four worst cases (facing maximum temperatures of 15.5°C) (Santamouris et al., 2014).

This situation leads countries like Portugal, Italy, Spain and Greece to often present excess winter mortality rates counterintuitively higher than in Finland and Sweden (Barnett et al., 2005). Healy et al. (2004) identified Portugal as the European country with the highest percentage of variation in mortality, with a 25% excess in winter deaths (EU Energy Poverty Observatory, 2019; Healy and Peter Clinch, 2004).

Different subjective indicators based on self-reported dissatisfaction can also be used, with regard to arrears on energy bills, poor housing conditions (such as leaking roof, damp walls or rotten windows) or inability to keep the home adequately warm (Atanasiu et al., 2014; Horta et al., 2018; Seebauer et al., 2019). Maps based on these indicators, retrieved by the EU Energy Poverty Observatory (Figure 1 to Figure 4), reveal Portugal as one of the most affected countries in Europe. In 2018, around 27% of portuguese citizens declared to live in an inadequate house with leaking floor or damp on walls (only Cyprus exhibited worse conditions) and 19% was unable to keep home adequately warm. As a small reassurance, this percentage has been steadily decreasing since 2007, when 42% declared their inability to adequately warm their home (EU Energy Poverty Observatory, 2019; European Commission, 2016).

Finally, numerous studies tackle energy poverty as a multi-dimensional issue that is influenced by several factors including occupants' behaviour and attitudes to achieve a given level of comfort (Aranda et al., 2017; Castaño-Rosa et al., 2020a, 2020b; Seebauer et al., 2019). These factors highly depend on the socio-economic situation of the specific households, making it difficult for individual indicators to express their reality. Castaño-Rosa et al. (2020a) propose to focus on the concept of vulnerability, in order to unify the various indicators expressing fuel poverty and expand their scope of action by using three dimensions: monetary cost, energy consumption and thermal comfort (Castaño-Rosa et al., 2020a).

Similarly, Simoes et al. (2016) propose a methodology to assess the share of population at risk of fuel poverty for 29 municipalities in Portugal based on indicators of economic and social vulnerability, (such as income, level of education, unemployment rate and number of inhabitants above 65 years old) as well as on an estimate of heating and cooling gap, the difference between the theoretical energy consumption required to satisfy comfort conditions and the actual lower consumption of deprived households. Results show that, on average, 22% of the inhabitants are potentially fuel poor regarding the satisfaction of their dwellings' heating needs and 29% regarding cooling needs (22% and 25% respectively for Lisbon Region) (Simoes et al., 2016).

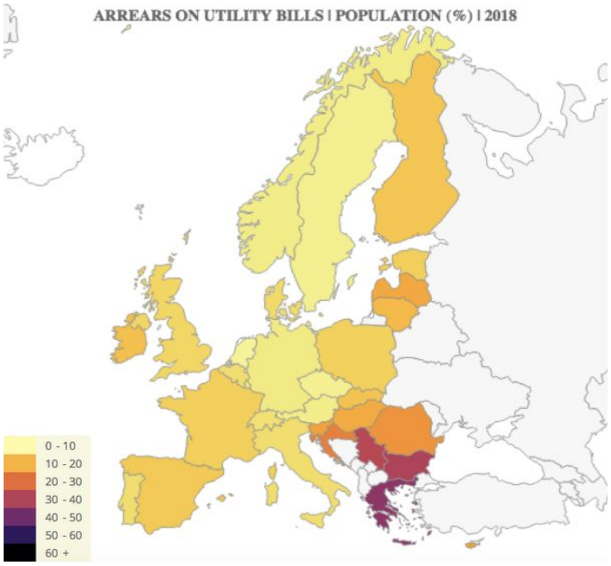


Figure 1: *Share of EU members' population having arrears on energy bills in 2018 (4.5% in Portugal)*

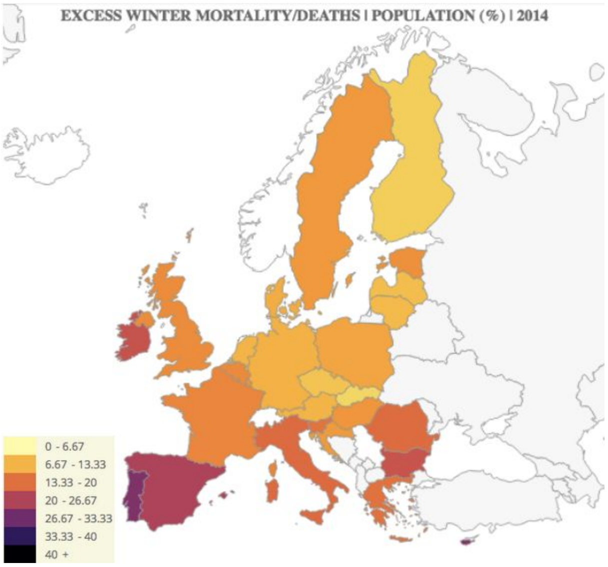


Figure 2: *Share of EU members' excess winter mortality in 2014 (24.9% in Portugal)*

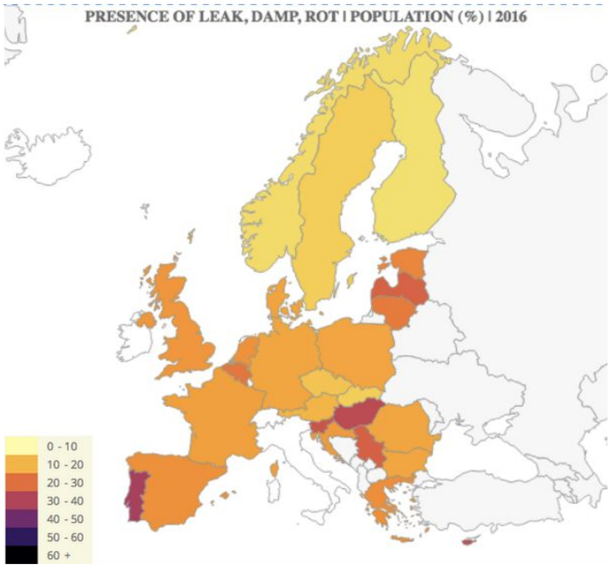


Figure 3: *Share of EU members' population living with leak, damp or rot in 2016 (31.3% in Portugal)*

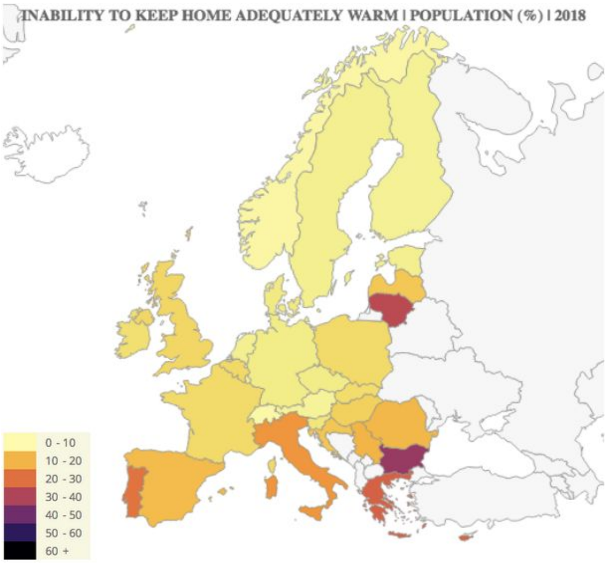


Figure 4: *Share of EU members' population unable to keep home warm in 2018 (19.2% in Portugal)*

Even if not all low-income households are energy poor, monetary deprivation certainly intensifies the risk of energy poverty mostly by affecting the housing quality (Seebauer et al., 2019). Specularly, the condition of energy poverty is not equitably distributed within all the population, but it mostly affects households with lower income.

Figure 5 to Figure 8 show the distribution of different EP indicators according to income in Portugal (in green) and compare it with the EU average (in blue), revealing strong income disparities for all indicators.

If the occurrence of arrears is evidently similar in both geographical boundaries (Figure 5), the share of people unable to keep home warm is also similarly distributed, although the values are twice as much for Portugal than for the EU (Figure 6). Indeed, the value for portuguese poorest group (decile 1 - 40.8%) is twice its average (20.4%) and 13 times higher than the corresponding richest fraction (decile 10 - 3.1%); as a comparison, for EU the highest value (19.1%) is more than twice the average (7.8%) and around 9 times higher than the lowest (2.1%).

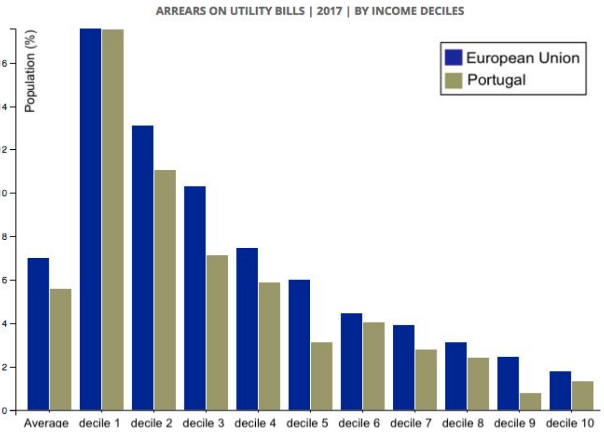


Figure 5: *Share of population disaggregated by income decile having arrears on energy bills in EU (blue) and Portugal (green) in 2017*

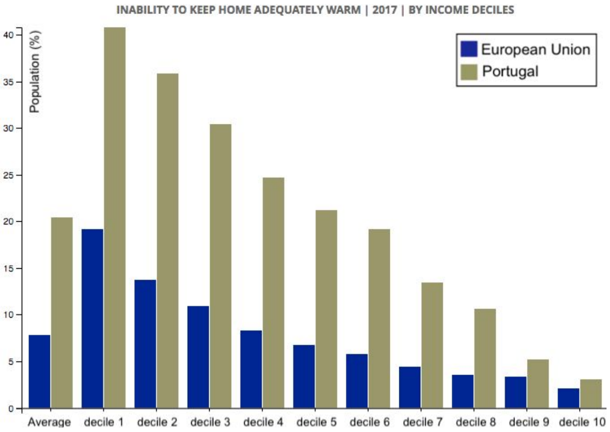


Figure 6: *Share of population disaggregated by income decile unable to keep home adequately warm in EU (blue) and Portugal (green) in 2017*

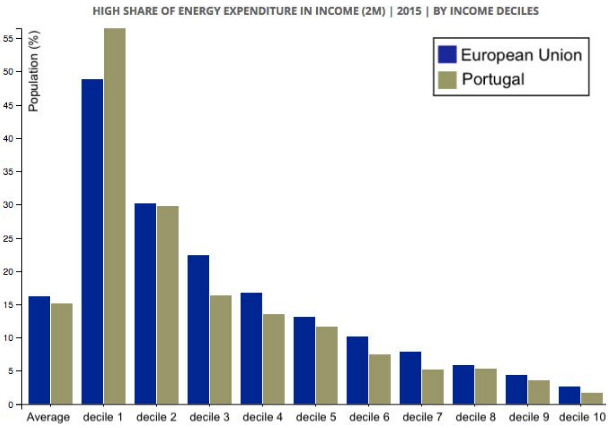


Figure 7*: Share of households disaggregated by income decile whose share of energy expenditure in income is more than twice the national median in EU (blue) and Portugal (green) in 2015*

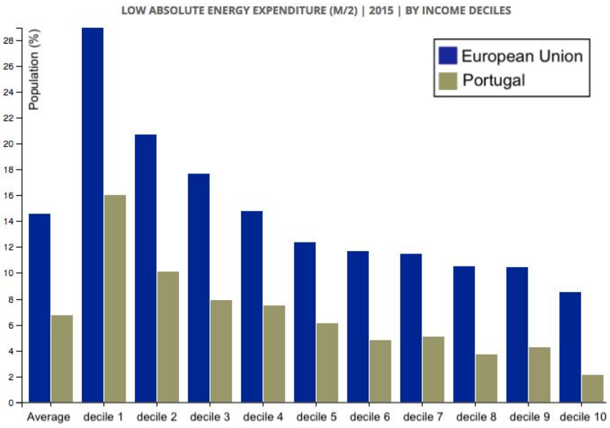


Figure 8*: Share of households disaggregated by income decile whose absolute energy expenditure is below half the national median in EU (blue) and Portugal (green) in 2015*

The real inequality emerges when looking at the incidence of high energy expenditure on income (Figure 7), in this case 56.5% of portuguese population in decile 1 is affected versus just 1.7% (33 times lower) of those in decile 10. While the average share for the EU is very similar to the portuguese (16.2% and

15.2% respectively), the gap between decile 1 (48.9%) and decile 10 (2.7%) is much lower (18 times), albeit still very high.

Finally, the only index for which Portugal regularly shows lower values than the EU is the share of low absolute energy expenditure, representing abnormally low values of less than half the national median (Figure 8). This indicator can, though, reflect two opposite situations: high energy efficiency standards or households dangerously under-consuming energy, reasonably applicable to low income deciles.

The tenure type also influences the incidence of energy poverty indicators, with people living in conditions of reduced or free rent being the most affected by arrears (Figure 9) and inadequacy of heating conditions (Figure 10), both in EU and Portugal. In Portugal, for example, the inability to adequately warm home is more commonly reported by social housing residents and private tenants (33% and 25% respectively) than by home-owners (17%) (EU Energy Poverty Observatory, 2019).

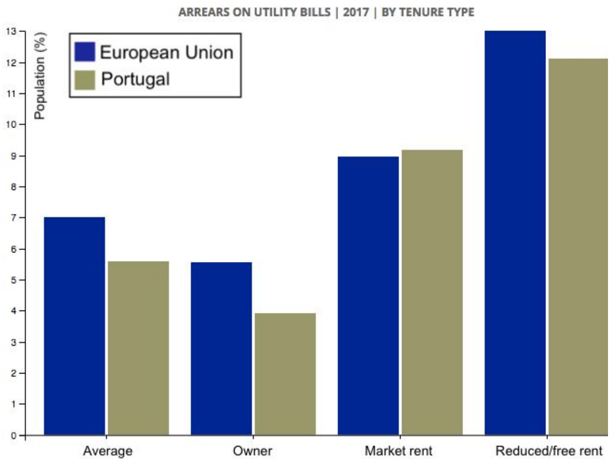


Figure 9: *Share of population disaggregated by tenure type having arrears on energy bills in EU (blue) and Portugal (green) in 2017*

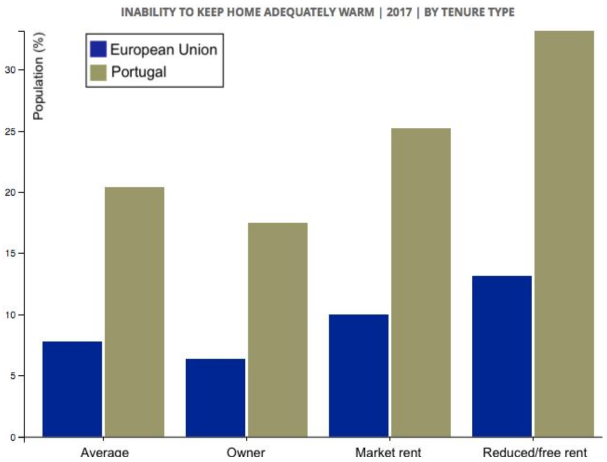


Figure 10: *Share of population disaggregated by tenure type unable to keep home adequately warm in EU (blue) and Portugal (green) in 2017*

In its analysis of low-income households in Athens, Santamouris et al. (2014) found a correlation between the income and the level of insulation of the envelope, expressed by the thermal conductance (measured in W/K); implying that the higher thermal comfort experienced by wealthier households is due to the better insulation of the building they live in, more than their greater ability to buy and consume energy. The same study shows how in a situation of economic insecurity, as the one brought by the 2008 financial crisis, vulnerable households reduce both their thermal comfort and their energy consumption (Santamouris et al., 2014).

It is interesting to note how, despite living in inefficient dwellings, low-income households still consume considerably less energy than higher-income households, even in cold and wealthy countries like Austria (Seebauer et al., 2019).

In conclusion, casting aside economic concerns related to energy bills, living in conditions of energy poverty implies suffering thermal discomfort and poor levels of Indoor Air Quality (IAQ). As a consequence, the energy vulnerable population is more prone to suffer health conditions, both physical (cardiovascular and respiratory) and mental (depression and stress, especially in young people) (Santamouris et al., 2014) as well as social exclusion, poorer diets, more hospital admissions and development, educational and psychological problems in children (Barnett et al., 2005; Peralta et al., 2017). In the winter from 2009 and 2010, Vasconcelos et al. (2011) surveyed portuguese inpatients that had suffered any form of acute coronary syndrome to find out that only half of those who felt the symptoms in a indoor place reported to have some sort of air heating device (an electric radiator in 26% of cases) and only half of them had used it last winter, suggesting poor housing conditions and fuel vulnerability as contributory causes (Vasconcelos et al., 2011).

These issues translate into a societal problem in terms of increased risk of poverty, increased expenses for the National Health Service (NHS) and the dissolution of social fabric.

Additionally, global warming is going to generate a dangerous positive loop: ever hotter summers will either cause higher thermal discomfort, thus increasing the vulnerability to energy poverty, or higher energy demand for cooling, boosting carbon emissions and global warming itself.

2.2 Energy retrofitting in social housing

Fuel poverty can be mitigated by interventions that aim to increase incomes, regulate fuel prices or improve the energy efficiency of households (Atanasiu et al., 2014). However, when energy costs are not the main concern, the only remaining options involve increasing energy efficiency, which in turn also decreases the carbon footprint of the household involved.

Specifically, passive architectural interventions such as energy efficiency facade retrofitting (EEFR) have shown the strongest potential to tackle fuel poverty (Camprubí et al., 2016; Peralta et al., 2017). Passive retrofit measures improve the thermal properties of the envelope by adding an insulation coat to walls and roofs or replacing the windows with high performing ones. These interventions manage to decrease the winter thermal load required to maintain a comfort temperature inside the house and to eliminate the moisture pockets causing the formation of mold or leakages. EEFR interventions have demonstrated to increase thermal comfort (Curado and de Freitas, 2019; Mancini et al., 2016; Monteiro et al., 2017) and to reduce cold-related morbidity and mortality rates (Peralta et al., 2017).

In a Mediterranean climate, passive measures alone could lead to substantial decrease in thermal dissatisfaction, in line with the margins of tolerance set by Europe (European Standards, 2012). Drawing up from a case study in Seville (Southern Spain), Curado and de Freitas (2019) have explored the potential of passive retrofit measures to reduce thermal discomfort of social housing tenants across the Iberian peninsula; results for Lisbon show that, through the concept of adaptive comfort, passive retrofit can bring the level of dissatisfaction below 15% (CAT. III - EN 15251) both in summer and in winter (Curado and de Freitas, 2019).

The social housing stock presents significant room for improvement on the basis of the generally poor energy performance of the buildings, the high vulnerability of the residents and the predisposition of the owner (public administrations) towards renovation.

In this regard, Escandón et al. (2016) have classified and compared five social housing blocks in different climatic zones of Andalucia in order to assess their energy performance; all the buildings were constructed between 1950 and 1980 and thus presented similar obsolete technical conditions $(wall\ U = 1.5 - 1.7\ \frac{W}{m^2 \cdot K}$ $window\ U = 5.7\ \frac{W}{m^2 \cdot K})$. Data collected reveal for all cases much higher values than those allowed by national standards both for heating demand (2.4 to 5 times higher) and energy consumption (2.6 to 3.8 times), with variations mostly depending on the climatic conditions (Escandón et al., 2016).

Various studies focusing on social housing in the Mediterranean climate have verified that passive measures alone can reduce the thermal load between 45% to 80% in winter (Mancini et al., 2016; Monteiro et al., 2017; Serrano-Lanzarote et al., 2017; Suárez and Fernández-Agüera, 2011) and between 30% to 48% in summer (Mancini et al., 2016; Serrano-Lanzarote et al., 2017; Suárez and Fernández-Agüera, 2011), resulting in a reduction in the annual energy demand between 36% to 63% (Mancini et al., 2016; Monteiro et al., 2017; Serrano-Lanzarote et al., 2017; Suárez and Fernández-Agüera, 2011). Considering energy savings to pay back the investment, those retrofits are characterized by payback times between 11 to 25 years (Mancini et al., 2016; Semprini et al., 2017).

To give some examples, Mancini et al. (2016) analysed a deep energy retrofit involving 700 low-income households in Rome, obtaining a 70% lower winter heating load (almost entirely covered by PV-Heat Pump hybrid system) and a 63% lower annual energy demand, with an investment of 670.000€ to be paid back in 15 years (Mancini et al., 2016).

Within the context of the european project Sharing Cities, Monteiro et al. (2017) simulates a retrofit 10 building in Lisbon without a central heating system, involving 248 households suffering from poor air quality, severe temperatures and mold. By insulating the envelope and replacing the windows, it was possible to reduce the energy demand by 36% and the winter heating load by 80%, thus increasing comfort by 5-8% for all the categories listed in EN 15251 (Monteiro et al., 2017).

Still building retrofits must undergo several of different nature:

- economical barriers, concerning the high upfront costs and long payback periods typical of building retrofitting;
- financial barriers, representing the lack of access to available and affordable finance mechanisms;
- informational barriers, affecting some of the stakeholders involved in the value chain of building retrofitting in terms of regulatory framework, state-of-the-art or operation and maintenance;
- behavioral barriers, not affecting directly the willingness to invest (e.g. unavailability to leave their houses or endure the annoyance when works are required) (Monteiro et al., 2017; Semprini et al., 2017).

People living in a rented house (30% of EU population) may also see conflict arise from the split-incentives dilemma, since the tenants would have immediate benefits while the owner would only obtain them in the long-run (Monteiro et al., 2017).

An additional obstacle often encountered in research is the so-called 'performance gap', that is the difference between the energy performance improvement estimated through simulation and the real performance of a building after the retrofit measures are completed. The reasons for this occurrence are multiple and difficult to identify, but clearly related to the inability of technical standards to represent the diversity of real occupants' behaviours. A rebound effect can derive from the monetary savings caused by the retrofit, in particular for Northern European countries, inducing the household to spend those savings into energy intensive activities (e.g. increase in the indoor temperature or the use of electric equipment). On the other side, prebound effects can also occur when users spend less time in the dwellings than what is established by the standardized use patterns of the different countries (Escandón et al., 2017).

Furthermore, the estimation on energy consumption as proposed by the national directives is based on the assumptions that comfort level is maintained within tolerable boundaries. As already discussed, this is often not the case for low-income households in a Mediterranean climate that scarcely rely on a heating system, suggesting that those households consume much less energy than the estimations made.

In an aforementioned study, Santamouris et al. (2014) calculated the average heating consumption of a low-income greek household is around 1,386 kWh per year (Santamouris et al., 2014), as a comparison the yearly average consumption of a Spanish multi-family dwelling calculated by the national standard is 3,673 kWh (Escandón et al., 2017).

All the above reduces the energy savings normally guaranteed by passive retrofitting, making the investments less effective due to excessive payback periods. Public health or fuel poverty are not always the primary concerns of energy efficiency retrofitting policies, so that the benefits in thermal comfort and health recovery are often neglected because of its non-monetary nature (Monteiro et al., 2017). This may result in exclusion of vulnerable groups (less affluent and fuel poors) from subsidy schemes (Camprubí et al., 2016) and further degradation of the already inefficient public housing stock..

The research for cost-optimality is an essential step of the retrofit plan, since it helps to enhance the appeal of the investment. Within the many technical solutions available on the market, the decision-making approach suggested by the EU looks for the minimization of the life-cycle cost (LCC) over the 30 years following the renovation (EU, 2012).

When budget or will restrictions do not allow for big investments, however, the cost-optimization frequently relies on the traditional shorter-minded concept of payback time. Still, a prioritization based on the cheapest options is less convenient than any other methodology. In this sense, Aranda et al. (2017) compare different combinations of 54 available measures with a budget limited to 5,500€ split between tenants and the public ownership, the study verified that energy savings derived by a cheapest-option classification were 20% lower than those based on the minimization of payback time (Aranda et al., 2017).

For the portuguese context, Eskander et al. (2017) developed an optimization method to maximize the energy savings at a minimum installation cost, revealing the benefits of different energy efficiency measures, here ordered by budget available: insulation of external walls and LED lights (low budget, with payback in less than 3 years), with the addition of an efficient Heat Pump (medium budget, payback in 4 years) and eventually the substitution of windows and PV production (high budget, payback in 7 years) (Eskander et al., 2017).

Studies that compare different degrees of retrofit interventions, from simple window replacement to deep retrofits meeting nearly-Zero Energy Buildings standards (usually classified as mild, moderate and intense), tend to agree on the higher benefits of moderate interventions (with 20-50% savings and short payback time) (Belpoliti and Bizzarri, 2015; Semprini et al., 2017; Serrano-Jimenez et al., 2017).

Serrano-Jimenez et al. (2017) integrated the results of energy simulations of 600 dwellings in Seville with a survey directed at 300 residents; moderate interventions revealed able to guarantee high enough savings while satisfying the preferences expressed (affordable passive measures on windows and walls) and the budget availability (less than 3,000€ per household for 81% of respondents) (Serrano-Jimenez et al., 2017).

Belpoliti and Bizzari (2014) developed a parametric method to assess the performance of the social housing stock of Emilia-Romagna region (Northern Italy), claiming the advantages of simple substitution of windows and heating system (39% energy savings) over the addition of envelope insulation or a combination of the two claiming (49% and 74% respectively), in accordance to the much shorter payback time (8 years versus 17 and 21) (Belpoliti and Bizzarri, 2015).

However, referring to a case study in Porto (Portugal), Ferreira et al. (2014) indicate that the transition between cost optimality to nZEB can occur without major difficulties, through the introduction of renewable energy systems (RES) on buildings that meet the cost-optimal levels (Ferreira et al., 2014).

Likewise, Semprini et al. (2014) establish that passive deep renovations aiming to nZEB criterias (through volumetric addition in this case) are not competitive when looking at the payback time (higher than 40 years), nonetheless competitiveness may arise when coupling interventions with RES systems or when looking at side benefits that are usually not accounted (Semprini et al., 2017).

Long payback times present an issue also for conventional retrofits, to overturn this and boost the ambitions of public energy retrofitting, some have proposed to translate non-monetary benefits of retrofitting into the calculations of the payback time (Castaño-Rosa et al., 2020b; Semprini et al., 2017). The improvement in IAQ would lead to better health conditions for the tenants, which would in turn reduce the pressure on the NHS and the related public expenses. Through their Index of Vulnerable Homes, Castaño-Rosa et al. (2020a) evaluate the amount of money saved by the NHS after the retrofit of a social housing block in Southern Spain, concluding that those savings could pay back the investment required for the case study in around 3 years (Castaño-Rosa et al., 2020a, 2020b).

This kind of strategy requires intersectional policy efforts analogous to the Warmth and Wellbeing Scheme, launched under the Irish Government's Strategy to Combat Energy Poverty, in which free energy efficiency measures are delivered to people affected by a chronic respiratory disease ("Warmth and Wellbeing," 2017).

On a similar track, but much more complex to quantify, is the idea to finance retrofit projects with part of the enormous investments that have just started being allocated for climate change adaptation, considering the high amount of carbon emissions that could be saved renovating the existing building stock (Ürge-Vorsatz and Herrero, 2012).

Public administrations play a crucial role to promote energy retrofitting both by encouraging private investments, through monetary incentives and tax deductions, and by intervening directly on the public housing stock they own. In the last case, taking into consideration the high amount of public buildings in need for renovation, it is important to understand which households are the most affected and should receive priority of intervention.

Different studies propose integrated methodologies looking both at architectural concerns, as audited by technical experts, and to the perception of residents (Serrano-Jimenez et al., 2017) or the presence of vulnerable groups (like unemployed or elders) (Castaño-Rosa et al., 2020a; Serrano-Jiménez et al., 2019), making use of tools typical of social sciences.

Alternatively, Fabbri (2015) integrated data from Energy Performance Certificates (EPC), official energy prices and income statistics on the population to develop the Building Fuel Poverty Index, adopted to distinguish subjects that can afford to pay building energy refurbishment from those in need for public support (Fabbri, 2015).

2.3 Building stock characterization

Simulation tools can provide accurate data on energy demand and thermal comfort in order to target those buildings which could benefit from retrofitting more precisely. These tools require a vast amount of detailed data on at least physical characteristics, energy consumption, occupation and use of the dwellings. Projects like the European Building Stock Observatory (EU 2020) and the national systems of EPC (SCE 2020) are working to extend the scope and detail of the limited information that could be retrieved by national statistical datasets (Monteiro 2018).

Swan et al. (2009) identify two main configurations that energy simulation models at an urban scale can assume: top-down (TD) and bottom-up (BU). Top-down models determine the effect on historic energy consumption of long-term changes of macroeconomic indicators (such as GDP, employment rates and price indices), climatic conditions, construction/demolition rates, appliance ownership and population density. Bottom-up models, on the other side, build up from input data from individual households or groups of buildings to extrapolate at a regional or national level (Swan and Ismet Ugursal, 2009). Bottom-up approaches enable to extend the analysis on buildings lacking historical data, but as a counterpart they require a higher level of detail in the input data.

A further classification within bottom-up approaches refers to black, grey and white-boxes (De Coninck et al., 2016). Black-box or statistical methods (SM) rely on historic measured data and use different kinds of regression analysis to capture the correlation between energy consumption and particular end-users. White-box or engineering methods (EM) are based on the physical knowledge of the building and the technical systems under analysis and use thermal balance equations to predict the energy consumption and indoor comfort. Finally, grey-box or hybrid methods (HM) can be identified as those approaches combining the physical insights of the building with parameters estimation based on measured data (De Coninck et al., 2016; Monteiro, 2018; Swan and Ismet Ugursal, 2009).

Bottom-up approaches focus on a deep analysis of a few case studies assumed to be representative of the whole target stock, as derived from statistical data at national and regional level and, exceptionally, on experts' knowledge (Belpoliti and Bizzarri, 2015; Vasconcelos et al., 2015).

On the same track, in 2010 the European Union established the need to characterize the available building stock through the development of representative reference buildings within the framework of the EPBD recast (2010/31/EU). This measure allows to assess the overall potential of retrofitting for the specific context and even develop standardized measures that can be replicated (Vasconcelos et al., 2015).

Using the nomenclature proposed by Corgnati et al. (2013), the approach towards the definition of such reference buildings can follow three different patterns (Ballarini et al., 2014; Corgnati et al., 2013; Monteiro et al., 2015; Vasconcelos et al., 2015):

- Real Building (RB) methodologies (also "Real Average Building") select a real existing building with characteristics similar to the average obtained by a statistical analysis, the RB thus represents the most typical building in a specific category;
- Example Building (EB) methodologies (also "Real Example Building") create a virtual building which includes the most commonly used materials and systems on the basis of expert enquiries and other sources of information, the EB is used when no statistical data are available;
- Theoretical Building (TB) methodologies (also "Synthetical Average Building" or "Archetype") create a virtual building which includes the most commonly used materials and systems on the basis of statistical data, the TB is thus a statistical composite of the features found within a category of buildings in the stock.

Table 1 reports the scope of different studies making use of UBEM approaches to define reference buildings, specifying for each one which methodologies they use under the categories proposed before.

Whichever method is used, the effectiveness of the stock characterization into reference buildings is influenced by how many categories are used and which parameters are considered to define them.

Within the spectrum of the SusCity project, Monteiro (2018) proposes an Archetype method based on five parameters (main use, construction period, size-class, roof type and neighbourhood type) to assess the energy consumption of Lisbon housing stock: starting with a single reference building (Tier 0 - Residential), parameters are taken into account one by one to form new tiers and increase the number of archetypes.

While Tier 1 and 2, characterized by 5 and 8 archetypes respectively, show that the consideration of additional parameters have a relevant impact on the aggregated electricity consumption (+3 GWh and -2.4 GWh over a baseline of 83 GWh), Tier 3 and 4 do not show any significant improvement. These results suggest that introducing more detail improves the model predictions only up to a certain point, after which the small improvements would not be worth the extra-work required by data gathering (Monteiro, 2018).

Similar conclusions were obtained by Molina et al. (2020) after an extensive characterization of Chilean housing stock built on eight parameters, the study show that 496 archetypes are required to depict the whole stock but that the 90 most popular represent 95% of existing dwellings and only 29 cover 70% of them. The study, however, does not include an analysis of the representativeness of the reference building on the energy consumption that would be estimated (Molina et al., 2020).

Table 1*: Literature review on bottom-up approaches for building stock characterization*

	Method	**Reference**	**Scale**	**Scope**	**Case study**
(TABULA, 2012)	EM	TB / EB	National	Residential	15 EU countries
(Mata et al., 2014)	EM	TB	National	Building stock	UK, France, Germany, Spain
(Molina et al., 2020)	SM	TB	National	Residential	Chile
(Theodoridou et al., 2011)	EM	RB	National	Multi-family	Greece
(Kragh and Wittchen, 2014)	EM	TB / EB	National	Residential	Denmark
(Famuyibo et al., 2012)	SM	TB	National	Residential	Ireland
(Citterio, 2009)	SM	TB	National	Offices	Italy
(Ballarini et al., 2017)	EM	TB / EB	National	Residential	Italy
(Ballarini et al., 2014)	EM	TB	Regional	Residential	Piemonte (IT)
(Belpoliti and Bizzarri, 2015)	EM	TB	Regional	Social housing	Emilia-Romagna (IT)
(Eskander et al., 2017)	SM	TB	Regional	Residential	4 Portuguese cities
(Dall'O' et al., 2012)	HM	RB	Urban	Residential	Carugate (IT)
(Monteiro et al., 2017)	EM	TB	Urban	Residential	Lisbon (PT)
(Aelenei et al., 2016)	EM	TB	Urban	Residential	Lisbon (PT)
(Monteiro et al., 2015)	EM	TB	Urban	Building stock	Lisbon (PT)
(Vasconcelos et al., 2015)	EM	TB	Urban	Residential	Lisbon (PT)
(Gouveia et al., 2018)	EM	TB / EB	Urban	Residential	Évora (PT)
(Di Turi and Stefanizzi, 2015)	HM	RB	Urban	Social housing	Bari (IT)

Table 2 reports the main parameters considered to define building archetypes in different studies on building energy modelling. For additional information, Reinhart and Davila (2016) provide an extensive review on UBEM studies (Reinhart and Davila, 2016).

Table 2*: Literature review on the use of building archetypes for urban and regional building energy modelling*

	Use	**Age**	**Size**	**Climate**	**Roof**	**Floors**	**Heating**	**Other**	**Archetypes**	**Sample**
(TABULA, 2012)	-	X	X	X					430	~79M
(Mata et al., 2014)	X	X	X	X			X		593	~63M
(Molina et al., 2020)	-	X	X			X		X	496	~5.8M
(Theodoridou et al., 2011)	-	X		-					5	~2.5M
(Kragh and Wittchen, 2014)	-	X	X	-					27	~1.5M
(Famuyibo et al., 2012)	-		X	-	X		X	X	13	40,000
(Ballarini et al., 2017)	-	X	X	X					120	~11M
(Ballarini et al., 2014)	-	X	X	-					18	~900,000
(Belpoliti and Bizzarri, 2015)	-	X		-			X	X	10	58,395
(Dall'O' et al., 2012)	-	X	X	-	X	X		X	93	1,320
(Gouveia et al., 2018)	-	X	X	-	X	X		X	26	~3,000
(Monteiro et al., 2017)	-	X	X	-	X			X	18	3,259
(Aelenei et al., 2016)	-		X	-					17	1,816
(Monteiro et al., 2015)	X	X		X	X				13	-
(Di Turi and Stefanizzi, 2015)	-	X		-					5	~1,500

2.4 Policy framework in Lisbon

Lisbon has a long history of public housing, which have mostly covered the urgent need for relocation during the various waves of urban expansion. As an example, the construction of the bridge on the Tagus, happened during the economic boom of the 1960s, forced the relocation of thousands of informal settlers living in the Alcantara valley and on the slopes of the Monsanto park, where the new road infrastructure had to be built.

In 1960, according to a CML study, 43,470 people were living in 10,918 abusive barracks (Coelho et al., 2014). The evicted families, mostly migrants from the countryside looking for jobs, were moved to brand new neighbourhoods which were rapidly constructed mainly on the outer belt of the city.

The proliferation of informal settlement in the 1960/70s led during the CML to launch a new resettlement program in 1985 called *Plano de Intervenção a Médio Prazo para a Habitação Social de Lisboa* (*PIMP* - Mid-term Action Plan for Social Housing in Lisbon). The program, however, planned the construction of only 9,698 dwellings in the face of more than 15,000 households living in unsuitable conditions. To overcome the shortage, the CML claimed the help of Portuguese government, which in 1993 responded by presenting the *Programa Especial de Realojamento* (*PER* - Special Program for Relocation) (Costa and Subtil, 2013).

Still, the programs just described have fallen short on covering the need for adequate housing in Lisbon and, generally, in Portugal. The public offer on the housing sector is one of the lowest in Europe, representing only 3% of the residential housing building stock (Pittini et al., 2019). This can be a major cause for the bad living conditions of the vulnerable segments of the Portuguese population participating in the rental market. Indeed, between 1987 and 2011, 73.3% of the public investment for housing was allocated for subsidy schemes to support the purchase of private property. Instead, only 17.9% of the budget was used to promote the construction of public housing (Silva, 2019).

Furthermore, the major national programs for public housing, such as the *PER* and *PROHABITA*, were interrupted in 2011 for budget cuts justified by the economic crisis. Since then, the central government has delegated the promotion of public housing to municipalities. Public actors thus play a crucial role in the development of public housing, even if they tend to limit on modernising the public residential stock more than on enlarging it with new constructions or acquisitions of private properties.

In the case of Lisbon, the municipal enterprise Gebalis was founded in 1995 to promote and manage the residential properties owned by Lisbon municipality and currently manages 66 social neighbourhoods (*"Bairros sociais"*) accommodating 61,400 residents (Gebalis, 2020a). In 2015, Gebalis launched the program *Aqui há mais Bairro*, allocating 52.5M€ to major rehabilitation works which would improve the living conditions of around 26,000 people by 2021 (Gebalis, 2019).

In 2018, around 58,218 people (11.5% of Lisbon population) benefited from the program of Municipal Housing (*Habitação Municipal*) managed by Gebalis (Gebalis, 2020b), in which residences are provided at affordable rent (83.54€ per month on average) to needful households through a public bid. Gebalis is responsible for 22,520 accommodations (7% of Lisbon total) located in 67 municipal housing neighbourhoods spread around the city.

Two other rent relief programs are available in Lisbon: the Affordable Rent program (*Renda Convencionada*) and the Municipal Subsidy for Rent (*Subsidio Municipal ao Arrendamento*). The number of requests to all programs has been increasing in recent years, in the case of Gebalis it passed from 3,411 in 2013 to 6,312 in 2017 (Observatório de Luta Contra a Pobreza na Cidade de Lisboa, 2018).

3. Methodology

A holistic approach for the analysis and evaluation of retrofit measures on several social neighbourhoods in Lisbon requires the use of different approaches that evaluate energy consumption, thermal comfort and economic analysis. These approaches are presented next, being some based on the work developed by Castaño-Rosa et al. (2020a) and adapted to the Portuguese and Lisbon context, and others proposed by the authors. The case study and the approaches used in this paper are presented next. Figure 11 presents an orientative sketch of the methodology as a whole.

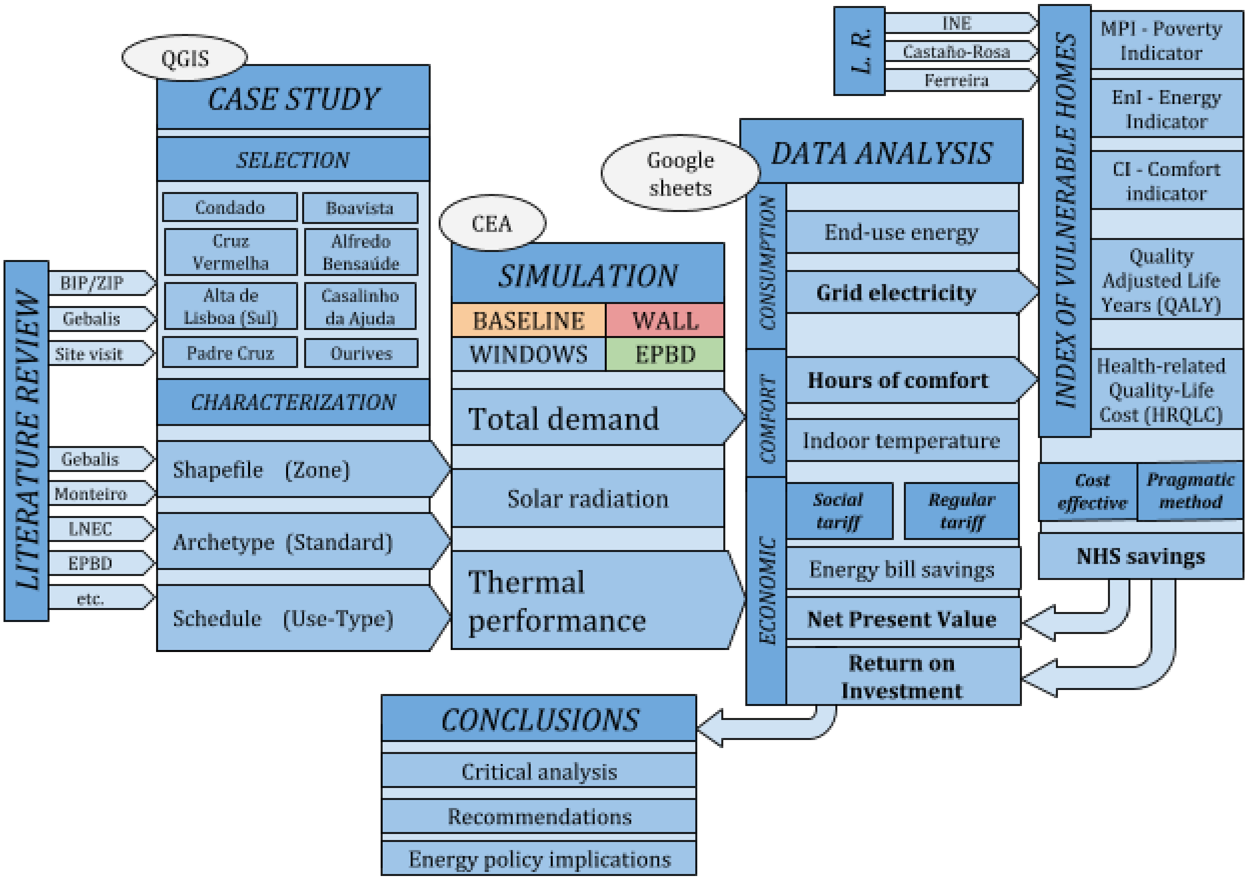


Figure 11: Overview of the methodology used in this work, outlining all the main steps (dark blue, italic and capital letters) the sources of information (light blue arrows) and the data serving as input or output of each step; in particular, the final outcomes presented as results are marked in bold

3.1 Case study: Lisbon social neighbourhoods

The climatic and socioeconomic conditions found in Lisbon are representative of other cities located in the Mediterranean region of many Southern-European countries, such as Spain, Italy or Greece.

These countries have been heavily affected by the 2008 economic crisis, which caused an extensive precarization of their vulnerable population in terms of purchasing power and access to affordable housing. As a consequence, their housing policy evolved from the promotion of private ownership (with subsidies on mortgages, for example) to the attraction of private investment in the sector, while relying on a limited offer of public housing (between 2% and 4%) (Housing Europe, 2019).

As commented in the "Introduction", mild Mediterranean winters make it possible for residents of inefficient houses to avoid using heating at the cost of suffering cold temperatures inside their home. Indeed, those Southern-European countries generally score poorly in indicators of fuel poverty based on comfort conditions, such as the excessive winter mortality and the inability to keep the home warm, but not so much on those based on energy expenses, such as the arrears on energy bills (apart from Greece).

The methodological procedure to identify and characterise the case study includes four main steps (which will be explained in detail in chapters 3.1 and 3.2), structured as follows:

(a) characterization of Lisbon's social neighbourhoods, using data provided by Gebalis, CML and a field visit;
(b) selection of specific neighbourhoods, according to the buildings' conservation status and the priority of intervention stated by CML;
(c) definition of building archetypes (or standards) for Lisbon;
(d) analysis of building characteristics.

These steps serve as a support to the next methodological steps (see chapters 3.5 to 3.8).

3.1.1 Definition of the case study

As a first step an appropriate case study was identified after a review of the current conditions of the public housing stock in Lisbon municipality. This information was crossed with a map drawn under the BIP/ZIP program (*Bairros e Zonas de Intervenção Prioritária de Lisboa*), which identified 77 areas of priority of intervention to reduce inequality within the city (CML, 2010a). The starting pool of eligible neighbourhoods consisted of the 38 social neighbourhoods managed by Gebalis which happened to be included in the BIP/ZIP maps (GEBALIS, 2011).

The conservation status of each neighbourhood was last evaluated in 2011, assigning "good/reasonable/bad" labels depending on the preservation status of the buildings (GEBALIS, 2011). Finally, numerous retrofitting actions planned for different neighbourhoods were reported in the "Integrated Program for the Renovation of Lisbon Municipal Neighbourhoods" (*Programa Integrado de Requalificação dos Bairros Municipais de Lisboa*), referring to the period 2015-2017 (Marques, 2015). This document also stated the average rent and the share of rent arrears encountered in those neighbourhoods.

Thus, the case study areas were selected within those neighbourhoods included in the BIP/ZIP map which likely showed worse than "reasonable" conservation conditions even after the renovation of 2015-2017.

A field visit was conducted on the nine neighbourhoods considered to be in worst condition to verify the data sources used and evaluate the building conservation status, analysing with a visual inspection the conditions of the building envelope (façade, roofs and windows) and building surroundings. This consisted in the exclusion of two neighbourhoods from the final case study because they show better conditions than expected, like Laranjeiras, or they are undergoing a demolition process, like Cruz Vermelha (Lusa, 2017).

After crossing the data provided by Gebalis and the field visit, seven neighbourhoods were chosen and their priority of intervention was established (graded with a Low/Medium/High scale).

Table 3 presents the evolution in size of the case study through the four steps of the selection process, by also breaking it down by the conservation status (or priority) of the neighbourhoods which compose it.

The location of the seven selected neighbourhoods is shown in Figure 12.

Figure 12: Location of selected neighbourhoods on theLisbon municipality map, obtained with QGIS

Table 3: Amount of neighbourhoods included in the case study, broken down by their conservation conditions (Reasonable to Bad) or priority of intervention (Low to High priority), through the four steps of the selection process described in this chapter

Source	**Selection criterion**	**"Reasonable" Low priority**	**"Reasonable/Bad" Medium priority**	**"Bad" High priority**	**Case study**
BIP/ZIP	Priority of intervention	/	/	/	**38**
(GEBALIS, 2011)	Conservation status	12	4	6	**22**
(Marques, 2015)	Renovations 2015/17	8*	4*	5*	**17***
Field visit	Visual inspection	2	1	4	**7**

*Deducted from the renovation programme described in the *Programa Integrado de Requalificação dos Bairros Municipais de Lisboa*

3.1.2 Characterization of selected neighbourhoods

According to Gebalis website, the case study area hosts more than 7,000 households and 22,000 residents. Table 4 provides a basic overview of the chosen areas of analysis regarding the demographics and economic situation of the residents, aggregated at district level.

A further characterization was necessary to distinguish different building typologies within the same area. To do so an historic review of each neighbourhood was carried out. The main sources of data for this analysis have come from Gebalis, however different blogs managed by citizen associations like *Bairro da Boavista - Lisboa (Pinto, 2010)* and *À descoberta das Hortas… no Bairro Padre Cruz* (Coelho et al., 2014) have provided vital information regarding the age of construction and the techniques used.

Table 4: Overview of conservation status (priority of intervention), demographics number of lots, dwellings and residents - from Gebalis website) and residents' economic situation (unemployment rate, average monthly rent and share of arrears in the rent payment - from Gebalis (2015)) of the seven neighbourhoods selected as a case study

	Priority of intervention	**Lots [/]**	**Dwellings [/]**	**Residents [/]**	**Unemployment [%]**	**Avg. rent [€/month]**	**Rent arrears [%]**
Alta de Lisboa (Sul)	**Medium**	46*	940*	2,751*	21%	97.67	44.6%
Alfredo Bensaúde	**High**	35	357	1,000	42%	97.20	58.8%
Boavista	**High**	568	1,521	4,379	19%	/	/
Casalinho da Ajuda	**High**	41	351	1,613	23%	/	/
Condado	**Medium/High**	79	1,440	4,917	21%	75.57	21.7%
Padre Cruz	**High**	897	1,939	6,084	18%	64.19	30.9%
Quinta do Ourives	**Medium**	53	584	1,719	16%	60.87	23.9%
TOTAL		**1,719**	**7,132**	**22,463**	**20%**	**79.10**	**36%**

*Calculated - Gebalis data refers to the whole Alta de Lisboa (Centro & Sul): 120 lots, 2,843 dwellings and 8,252 residents

The main outcome of this research are briefly proposed as follows:

- **Alta de Lisboa (Sul):** also “Alto do Lumiar”, born as informal settlements in the northern corner of Lisbon municipality, Alta de Lisboa was renovated in 1993 within the scope of *PER*; in 1998 the *PUAL* (*Plano de Urbanização do Alto do Lumiar* - Urbanization Plan of Alto do Lumiar) approved the expansion works to habilitate the area for 60,000 residents and designated the commercial name “Alta de Lisboa” (República Portuguesa, 1998), the original 2015 deadline was delayed after the real estate crisis; still, according to the evaluations made in the field trip, a part of the neighbourhood (Centro) was is better conditions then the rest (Sul) and was then excluded from the case study;

- **Alfredo Bensaúde:** built in 2001 within the *PER*, it is composed of three residential blocks isolated from the City by a major roadway, which also host the headquarters of Gebalis; the neighbourhood presents the highest unemployment and poverty within the case study, its residents identify serious social and health problems (Junta de Freguesia de Olivais, 2016) and the buildings are affected by serious degradation; the neighbourhood has also been a common scene of occupations (Roque, 2009) and evictions, even during the lockdown period imposed by COVID-19 (Gaudêncio, 2020);

- **Bairro de Boavista:** the old area is composed of around 500 small masonry (*alvenaria*) houses, which were built from 1961 to 1970 to relocate informal settlers living in Monsanto Park; two expansion waves happened in the periods 1978-1984 and 1988-1996, this last within the *PIMP*, reaching the actual configuration with around 1.000 households (Pinto, 2010); in 2010 the project of a new *Eco-Bairro Boavista Ambiente+* is approved by the *QREN* (*Quadro de Referência Estratégico Nacional* - National Strategic Reference Framework) to replace the old and deteriorated single-family houses (Lisboa E-Nova, 2019), the construction work started in 2016 (Gebalis, 2018a) and benefit from the contribution of the Sharing Cities project;

- **Casalinho da Ajuda:** built in 1970 to cover the relocation of settlers of Monsanto Park, then expanded in 1996 within the scope of *PER*;

- **Bairro do Condado:** originally called “Zona J de Chelas”, it was completed in 1983 after the design by Tomás Taveira in 1978 to combine commercial activities at the ground level with around 1,500 households in residential blocks and skyscrapers; the Municipality decided in 2011 the demolition and reconstruction of a zone described as *corredor da morte* (Death row), which became infamous for the dealing of drugs and the rivalry between gangs (Zona, 2011);

- **Bairro Padre Cruz:** similarly to Boavista, the old area of *alvenaria* was designed in 1959 to relocate around 1,000 households of informal settlers; the construction of a new area meant for 1,290 households started in 1988 within the *PIMP* program, reaching the status of the biggest public neighbourhood of the Iberic peninsula with a population of around 8,000 residents; the project for the replacement of the old *alvenaria* houses was approved by the *QREN (CML, 2010b)*, the construction work started in 2015 (Gebalis, 2018b) and benefit from the contribution of the Sharing Cities project;

- **Quinta dos Ourives:** built in 1970, it was expanded in 1996 under the *PER* program to host around 1,700 people; the majority of the buildings were renovated between 2006 and 2017 either entirely or through the replacement of old windows.

A shapefile containing Lisbon building stock, accessed through QGIS, was consulted to correctly identify to which buildings the information referred and aggregate them by similarity into groups (or proto-archetypes). Additional data on the number of floors and the lot surfaces were retrieved using both QGIS and CEA. Google Maps, Wikipedia and various newspaper articles have supported this activity, still the dataset could only be completed adopting different assumptions.

In particular, at first, the number of residents per household (density) was considered always equal to the neighbourhoods' averages. Similarly, the number of households per floor were assumed to be proportional to the lot surface occupied by the buildings.

The number of households per lot (compactness), the dwelling size, the living area per person and the number of buildings per group were calculated using the estimated parameters. Finally, the parameters were repeatedly corrected until the calculated number of buildings matched the value provided by Gebalis for each neighbourhood. Additional information is provided in Annex A.

The shapefile had to be adjusted to make it consistent with the sintaxis used by City Energy Analyst, the software selected to run the simulations. Thus, for each neighbourhood, three files were elaborated: "*zone.shp*", "*surroundings.shp*" and "*typology.xlsx*".

The first two are shapefiles containing the height and number of floors of, respectively, the buildings to simulate and the ones surrounding them; while the last is a fundamental database containing data on use, construction standard and year of the buildings. It is used by CEA to assign the correct parameters to each building and has to be converted into "*typology.dbf*" through a utility provided by the software.

3.2 Archetype definition

After collecting this data, a bottom-up engineering method inspired by the work of Monteiro (2018) was used to define building archetypes (or standards) for Lisbon. The archetypes are statistical composites of the features found within a category of buildings, each category is identified by two parameters: the period of construction and the size-class.

Four typical age ranges were defined according to the main changes in construction techniques and standards, especially regarding regulations on energy performance. Focusing on Portugal, the boundaries are represented by the *RCCTE* (República de Portugal, 2006), the first portuguese legislation on building performance passed in 1991, and the two *EPBD* recasts of 2006 and 2013 (Fragoso et al., 2018; INCM, 2006).

Distinctions in size-class (*single* or *multi-family*) could only be applied to the first age range (*1961-1990*), while the newest constructions reflect the preference towards big residential blocks for public housing.

Figure 13 summarizes the procedure just explained and expresses the representativity of each standard regarding the amount of buildings, households and residents. It can be noted how the old single-family houses, found in the older areas of Boavista and Padre Cruz, represent the vast majority of buildings (76%). However these only host a small fraction of people, while the majority (34%) live in multi-family buildings erected 15 to 30 years ago.

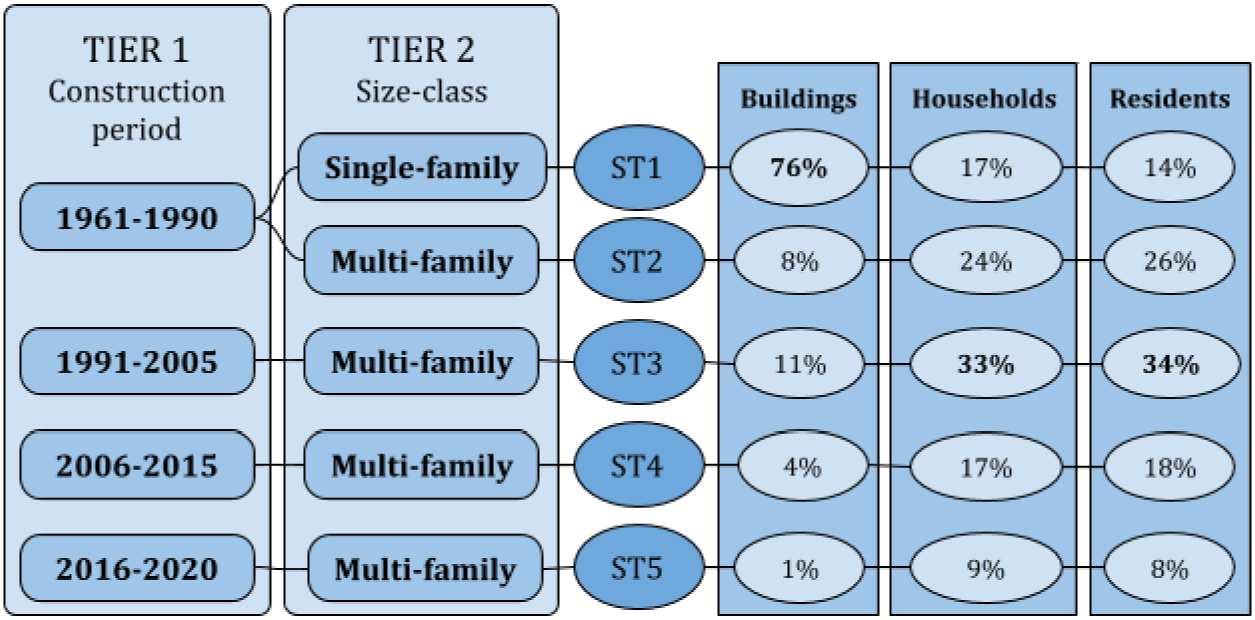


Figure 13: Definition of each construction standard (ST) by construction period (Tier 1) and size-class (Tier 2), together with their representativity regarding the amount of buildings, households and residents

Table 5 presents the overall heat transfer coefficients (*U-value* (W/m^2K)) assigned to the main envelope components for each standard. The values were retrieved from the *ITE 50* technical standard redacted by the National Laboratory of Civil Engineering (*LNEC)*, which reports average values for the thermal transmission coefficients of the building envelope elements (Santos and Matias, 2006).

For standards from 1 to 4, the selected components were chosen to make them consistent with the average U-value of each standard (*ref. U*) as calculated by Monteiro (2018). Also, the U-values for standard 5 were chosen to satisfy the EPBD requisites for major renovations.

Table 5: Overall heat transfer coefficients (U-value) of the main envelope elements of the Portuguese construction standards used for this study and the average U-value found for Lisbon's buildings (ref. U - from Monteiro (2018))

	Type	Description	U-value	ref. U		Description	U-value	ref. U
			(W/m^{2}K)				(W/m^{2}K)	
STANDARD1 **1960-1990** **SF**	**Ext. wall**	Light concrete, no ins. (LNEC_ITE50_II.1A)	**1.3**	0.96	**STANDARD5** **2016-2020** **MF** **(EPBD)**	L. concrete, 6cm EPS ins. (LNEC_ITE_II.2A)	**0.45**	0.50**
	Windows	Single glaze, metal frame (LNEC_ITE50_III.2)	**5.4**	5.2		Double, PVC frame, air-tight, low-emissivity (LNEC_ITE50_III.3)	**1.9**	2.80**
	Roof	L. concrete, no insulation (LNEC_ITE50_II.17)	**2.7**	2.63		L. concrete, 10cm EPS ins. (LNEC_ITE50_II.19A)	**0.35**	0.40**
	Floor	/	**0.9**	0.90		/	**0.5**	0.50**
STANDARD2 **1960-1990** **MF**	**Ext. wall**	Light concrete, no insulation (LNEC_ITE50_II.1A)	**1.3**	1.89	**STANDARD6** **EcoBairro** **Boavista**	L. concrete, 6cm EPS ins. (LNEC_ITE_II.2A)	**0.45**	/
	Windows	Single glaze, metal frame (LNEC_ITE50_III.2)	**5.4**	5.2		Double (Cool lite SKN 176), metal frame, air-tight (Navarra n18 200)	**1.6**	/
	Roof	L. concrete, no insulation (LNEC_ITE50_II.17)	**2.7**	2.63		L. concrete, 4cm XPS ins. (LNEC_ITE50_II.19A)	**0.62**	/
	Floor	/	**0.9**	1.56		/	**0.5**	/
STANDARD3 **1991-2005** **MF**	**Ext. wall**	Concrete, 4cm XPS ins. (LNEC_ITE50_II.2B1)	**0.65**	0.63	**STANDARD7** **EcoBairro** **Padre Cruz**	L. concrete, 8cm XPS ins. (LNEC_ITE_II.2B1)	**0.4**	/
	Windows	Double glaze, metal frame (LNEC_ITE50_III.2)	**3.3**	3.3		Double (Cool lite SKN 176), metal frame, air-tight (Extrusal A.040)	**1.4**	/
	Roof	L. concrete, 3cm XPS ins. (LNEC_ITE50_II.19A)	**0.74**	0.75		L. concrete, 4cm XPS ins. (LNEC_ITE50_II.19A)	**0.62**	/
	Floor	/	**0.9**	0.95		/	**0.5**	/
STANDARD4 **2006-2015** **MF**	**Ext. wall**	Concrete, 6cm EPS ins. (LNEC_ITE50_II.2B1)	**0.55**	0.56*				
	Windows	Double, metal, air-tight (LNEC_ITE50_III.2)	**2.9**	2.9*				
	Roof	L. concrete, 4cm EPS ins. (LNEC_ITE50_II.19A)	**0.69**	0.67*				
	Floor	/	**0.9**	0.84*				

**Assumed by extension from Monteiro (2018), which referred to the period 2006-2011*
***EPBD requirements for portuguese climatic zone I1 starting 1st of January 2016*

3.3 Retrofit scenarios

Table 5 also reports the U-value used for three additional standards (5, 6 and 7), which represent different retrofit options which will be explained hereafter.

Standard 5 consists in a theoretical building whose values of thermal transmission would be enough to satisfy the requisites imposed by the EPBD on the major renovations, defined as those impacting on more than 25%

of a building floor area. With this outlined, the EPBD requisites further divided into three passive retrofit scenarios assigned to all buildings of standards 2, 3 and 4 with the aim to simulate and compare them with the baseline:

- **Windows:** considering the replacement of all existing windows with high-performing ones which satisfy EPBD requirements, represented by double-glazed windows with a PVC frame, which has a U-value equal to 1.9 W/m^2K;
- **Wall:** considering the installation to all external vertical opaque surfaces of enough thermal insulation to satisfy EPBD requirements, represented by a light concrete wall with 6cm of EPS applied to the external surface, which has a U-value equal to 0.45 W/m^2K;
- **EPBD:** considering both previous scenarios, plus the addition to all horizontal external surfaces of enough insulation to satisfy EPBD requirements, represented by a light concrete roof with 10cm of EPS applied to the internal surface, which has a U- value equal to 0.35 W/m^2K, and a floor with a U-value equal to 0.5 W/m^2K;

Buildings of standard 1 were excluded since, for structural reasons, it would be unrealistic and certainly more expensive to perform any type of renovation action without having to redesign the buildings themselves. In this regard, plans to demolish these obsolete buildings and replace them with state-of-the-art apartment blocks, which would also provide satisfactory living conditions to their residents, were developed both for Boavista and Padre Cruz. Thus, standards 6 and 7 thus represent the design of the new constructions as proposed by the CML (CML, 2016a, 2016b). The plans are promoted as *Eco-Bairros* (Eco-Neighbourhoods) and fall into the scope of the Sharing Cities project, hence the thermal transmittance values were available from the technical sheets of each design component.
Additional information on the seven standards just described can be accessed in Annex B.

3.4 Use-type/schedule definition

Standard occupancy and system usage (heating, appliances and lighting) had to be defined in order to create the building schedules. The procedures will be explained separately for each element hereafter.
Further information is available in Annex C.

3.4.1 Occupancy

This study makes use of the occupancy profiles obtained from an online survey answered by 111 citizens living in the northern Lisbon metropolitan area, which focused on users' behavior on the use of energy for space heating, cooling and domestic hot water (Ferreira, Panao 2016).

The survey distinguished four main users living in Lisbon: student, employed, unemployed and retired. These profiles, that distinguish weekdays from weekends, are shown in Figure 14.

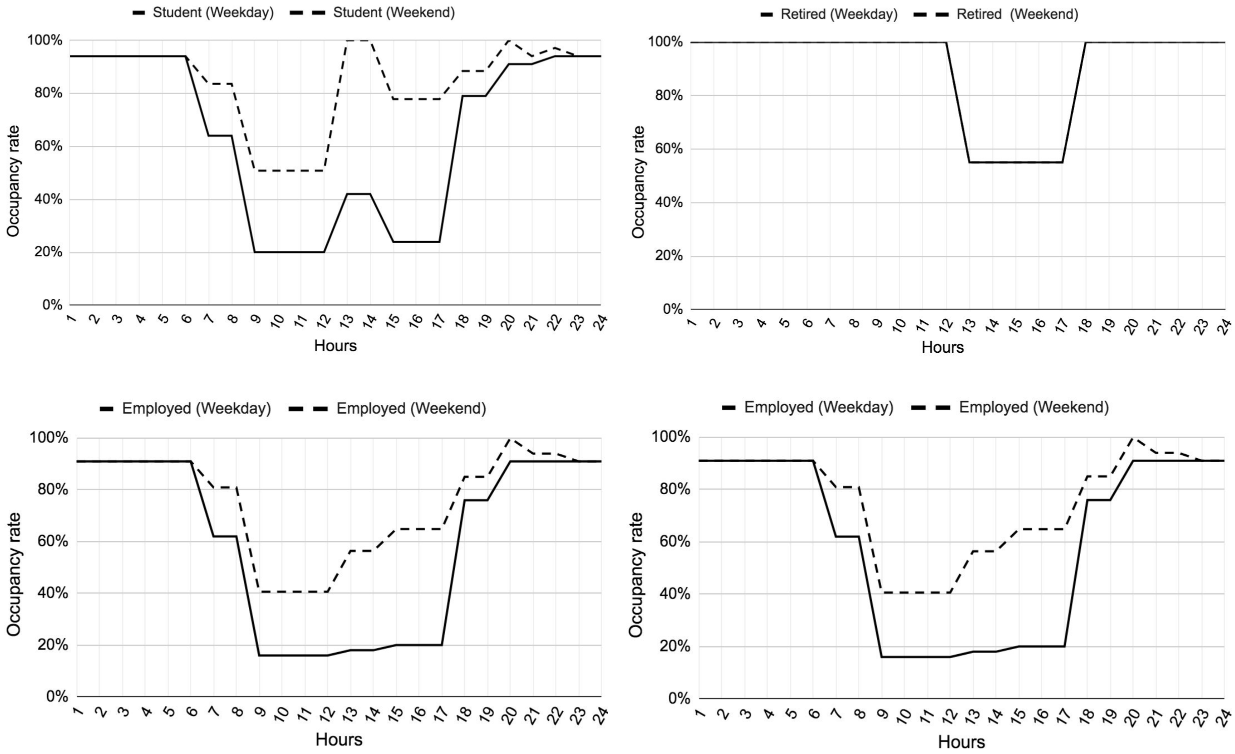


Figure 14: Occupancy profile, in weekdays (continuous line) and weekends (dashed line,) of the four reference users: Student (top left), Retired (top right), Employed (bottom left) and Unemployed (bottom right)

The occupancy rate was calculated for all neighbourhoods from data on the working situation of their residents provided directly from Gebalis. The categories examined by Gebalis were the four depicted before, plus "domestic worker", which was included into the "retired" category for the sake of simplicity. The resulting average thus differs for every neighbourhood, as can be seen in Figure 15 comparing the Quinta de Ourives with Alfredo Bensaúde.

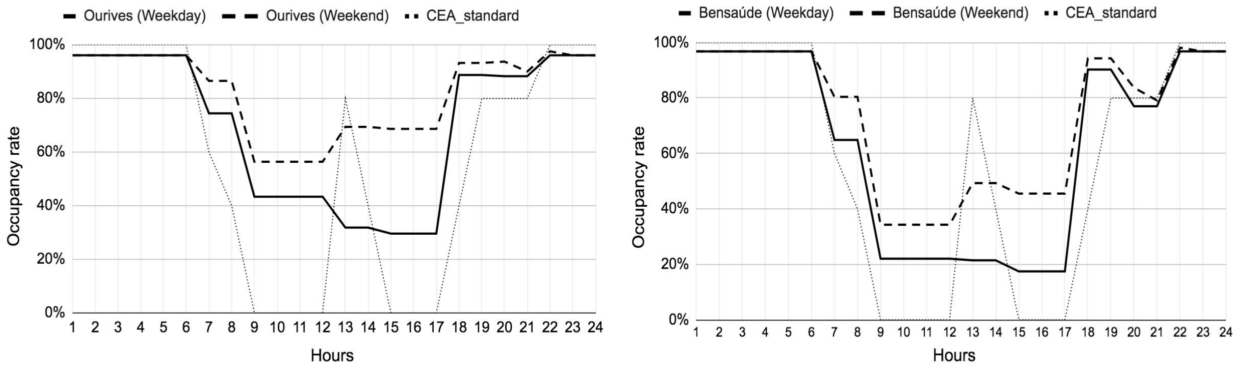


Figure 15: Neighbourhood's average occupancy profile of a reference user in Quinta do Ourives (left) and Alfredo Bensaúde (right), in weekdays (continuous line) and weekends (dashed line), compared with the reference profile proposed by CEA (dotted line)

The last shows lower levels of occupation since it hosts a younger population (24% students and 14% retired) than Ourives (16% students and 35% retired) and also suffers a much higher unemployment rate (42% versus 16%).

3.4.2 Heating system

A similar procedure has been used to define the heating schedule, starting from data on the probability of having the heating on hour by hour, obtained through the aforementioned questionnaire (Ferreira and Panao 2016). Then, from the average probability, specific profiles were assigned to the four categories mentioned before proportionally to their occupancy. Then again, a new average was calculated for each neighbourhood according to the user occurrence.

Finally, since CEA only accepts the conditions in which the heating system is set at two temperature levels (SETPOINT and SETBACK) or is kept off (OFF), the average probabilities higher than 0.5 were assigned to SETPOINT (here set to 20°C), those below 0.2 to OFF and the rest to SETBACK (set to 16°C).

In this case, the lack of sensitivity imposed by CEA means that all neighbourhoods result in the same heating schedule, regardless of their different demographics. Figure 16 shows the correlation between the probability profile derived from Monteiro (2018) and the resulting temperature setting, compared with the standard proposed by CEA.

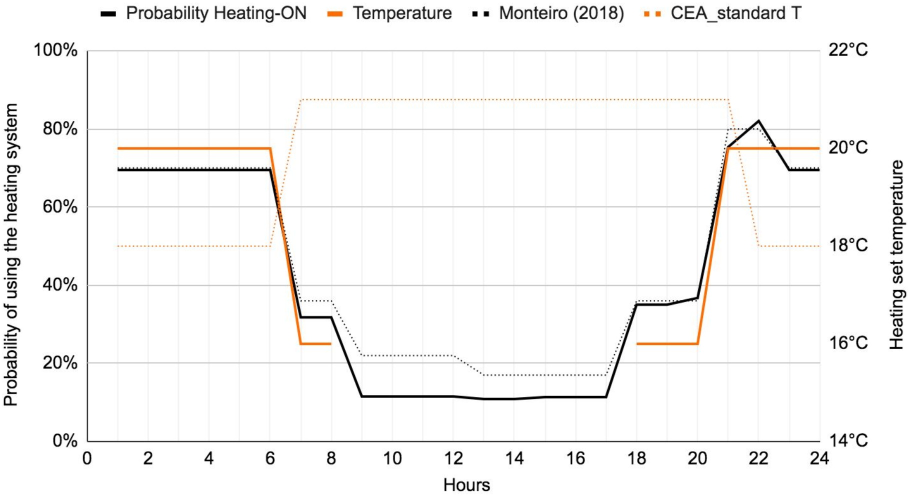


Figure 16: Probability of having the heating set ON (continuous black line) and corresponding temperature setpoint (continuous orange line) throughout the day, compared with the reference probability profile elaborated by Monteiro (2018) (dotted black line) and the reference set temperatures proposed by CEA (dotted orange line)

It has to be noted how the heating schedules and the setpoint temperatures just described are an extreme simplification of the actual heating behaviours of the residents of Lisbon public housing. In fact, according to the *IDEF 2015/2016* (*Inquérito às Despesas das Famílias* - Survey on Household Expenditure), not only 72% of portuguese households use autonomous heating systems (marked as “*Outro aparelho de aquecimento de ar”*), mainly small electric heaters, but around 20% do not own any heating system at all.

Additionally, this last measure rises to more than 40% for the poorest portuguese income quintile, a category that can reasonably represent the households under this study (INE, 2017). Hence, the share of ownership of the different heating systems for the first income quintile in Lisbon (*Q1 Lx*) was calculated from the first portuguese quintile (*Q1*) and the average ownership in Lisbon (*Lx*) and Portugal (*PT*) using Equation (1); results are shown in Table 6.

$$[Q1\ Lx] = [Q1] \cdot \frac{[Lx]}{[PT]} \tag{1}$$

This analysis unveils that around a third of the households under scrutiny do not use any kind of heating system, an assumption that will be taken in consideration in the process of assigning the schedules before the simulation and that will highly impact the results obtained.

As shown in Table 6, only a very small fraction of households own a system equipped with thermostats ("Central heating" or "Air conditioning"), which are a prerequisite under the only configuration accepted by CEA. The setpoint temperatures were then chosen in order to provide throughout the year a heating load similar to the actual heating conditions. These conditions were defined as using an electric heater with 2 kW of nominal power from the middle of November to the middle of March for 10 hours per day, which is derived from the probability profile adapted from Monteiro (2018).

A major throwback of this assumption is the lack of correlation between the indoor temperature and the heating use, making the punctual results of the simulation less reliable. As can be seen in figure 40, various days in April, May and October would still require some heating power to reach the minimum temperature of comfort, but since they fall outside the chosen heating season the model does not account for the power needed.

Table 6: Average ownership rate of different typologies of heating systems in Portugal (PT) and in Lisbon (Lx), compared with the average for Portuguese first income quintile (Q1) and Lisbon first income quintile (Q1 Lx - author's contribution)

Heating system type	**Ownership rate**			
	Portugal [PT]	**Lisbon [Lx]**	**Portuguese first income quintile [Q1]**	**Lisbon first income quintile [Q1 Lx]**
Central heating	16%	9%	7%	**4%**
Autonomous (Electric heater)	64%	72%	55%	**62%**
No heating system	20%	19%	38%	**34%**
Air conditioning	16%	19%	5%	**6%**

3.4.3 Appliances

The *IDEF 2015/16* also provided data on the ownership of the 22 most common electric appliances used for housework, communication and leisure; again this information was collected per geographical area and per income quintile, allowing the extrapolation of useful data for the study group (*Q1 Lx*).

17 of those appliances, plus lighting, were selected and divided into the following seven categories ($a \in A$) to build a schedule specific for the case study:

- **Always-on (ON)**: Fridge, freezer, television stand-by and Internet router;
- **Cooking (COOK)**: Electric stove and microwave;
- **Cleaning (CLEAN)**: Vacuum cleaner, washing machine, clothes dryer and dishwasher;
- **Small (SMALL)**: Television and computer monitor;
- **Battery (BATTERY)**: Phone and laptop chargers;
- **Occasional (OCC.)**: Sewing machine, home sound system and game console.
- **Lighting (LIGHT)**

A list of typical peak power (P) consumption of household appliances made by DaftLogic was consulted to assign a peak load to all equipment (DaftLogic, 2020). For categories "Alway-on", "Cleaning" and "Lighting", the estimated annual consumptions (EL_y) of an average portuguese household of 3-4 people were retrieved from a study from the Energy Agency of Seixal (AME Seixal, 2015) and used to calculate the daily usage of each appliance (h_{use}), taking into account the ownership rates referred to Portugal (*PT*); a household size of 3.5 people was considered as a reference for all the following calculations (e.g. per capita consumption). For the other categories the opposite reasoning was applied: first a reasonable daily usage was estimated (e.g. 1 h/d for COOK, 4 h/d for SMALL), thus the average annual consumption was calculated; both calculations used Equation (2) or its reverse.

$$\forall a \in A \qquad EL_{y,a} = P_a \cdot h_{use,a} \cdot \left(365 \tfrac{d}{y}\right) \cdot [PT]_a \tag{2}$$

Then again, using Equation (1), these calculations were adapted to the ownership rates of Lisbon's first income quintile (*Q1 Lx*); the impact of this assumption are shown in Figure 17 and Figure 18.

Figure 17 compares the per capita annual electricity consumption for appliances and lighting of the two groups with the reference per capita domestic electricity consumption in Portugal ($EL_{y,pc}$ - black line), which was $1,219.6 \frac{kWh}{y \cdot p}$ in 2017 (PortData, 2020a).

On the other hand, Figure 18 shows the total annual consumption of each equipment category for the two groups. Cleaning appliances contribute the most to the disparity, in fact, for example, only 27% of *Q1 Lx* members own a dishwasher compared to 53% on average in Portugal.

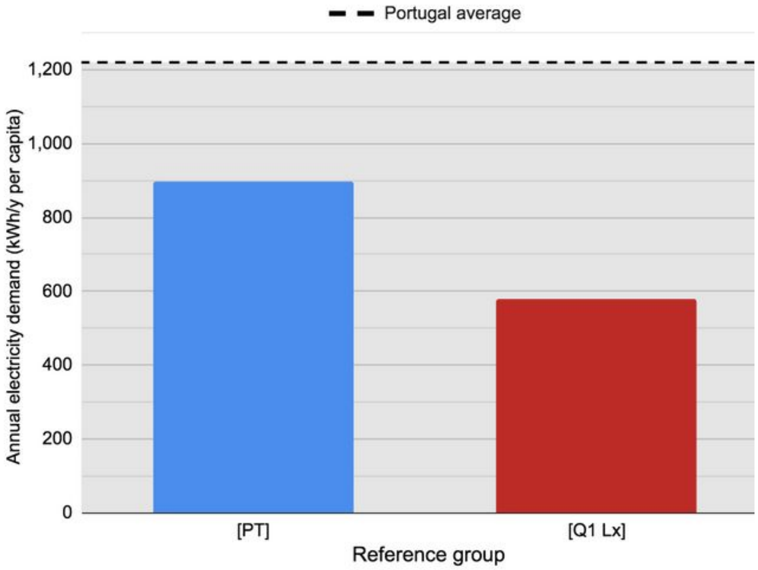


Figure 17: Estimated per capita annual electricity consumption for appliances and lighting, considering the ownership rate for Portugal (blue) and Lisbon first income quintile (red), compared with the reference per capita domestic electricity consumption in Portugal (black)

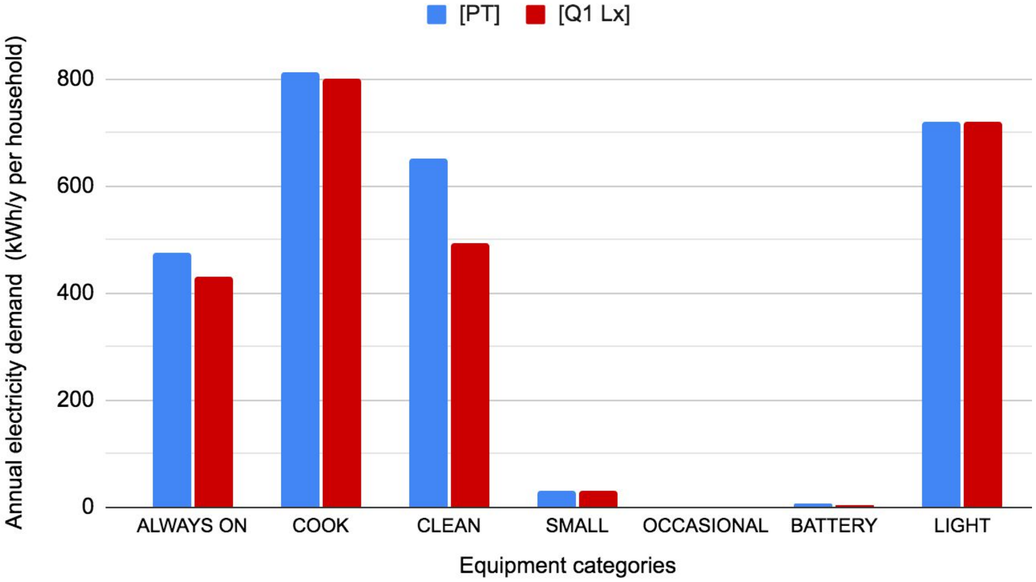


Figure 18: Estimated annual electricity consumption for each equipment category for a reference household of 3.5 residents, considering the average ownership rate for Portugal (blue) and for Lisbon first income quintile (red)

For each neighbourhood, the relative peak load (p) of each category, expressed in **W/m²**, was calculated dividing the peak power by the average household size previously calculated. Thus, the probability of use (pr_{use}) at every hour of the day was defined for all categories so as the sum would equal the daily usage earlier selected (h_{use}). The hourly loads (E_h), expressed in Wh/m², were then calculated as the sumproduct of the relative peak loads and the probability coefficients, as expressed by Equation (3).

$$\forall h = 1, \ldots, 24 \qquad E_h = \sum_{a \in A} (pr_{use} \cdot p_a) \tag{3}$$

Finally, the resulting hourly loads were corrected to make them proportional to the occupancy profile of each neighbourhood. These calculations were made separately for appliances and lighting.

The maximum hourly load was then selected and rounded up to define the peak loads of appliances (*Ea_Wm2*) and lighting (*El_Wm2*) required by CEA as inputs. The hourly loads were thus made dimensionless, as required by CEA, dividing E_h by the fictional maximum peak load. The peak loads were rounded up so that the probability profile was comparable to the standard one used by CEA; to do so the sum of the calculated dimensionless usage coefficients h_{use} had to equal 6 h/d, which is the sum of the standard coefficients of CEA. The resulting reference schedules are shown in Figure 19 and Figure 20.

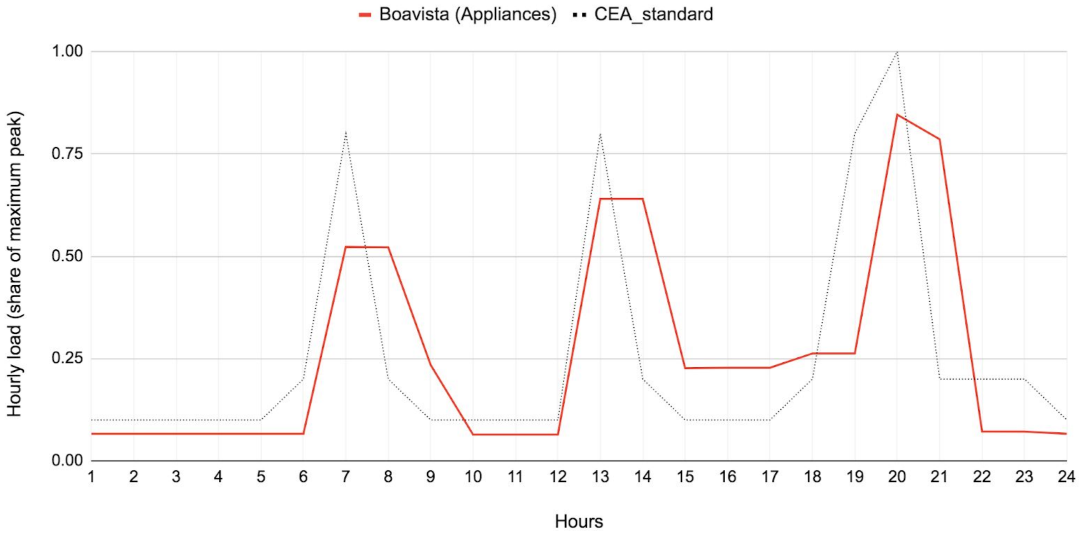


Figure 19: Reference usage profile of appliances (red) for Boavista (proportional to the neighbourhood's occupancy rate), expressed as a fraction of the maximum fictional peak, compared with the reference profile proposed by CEA (black)

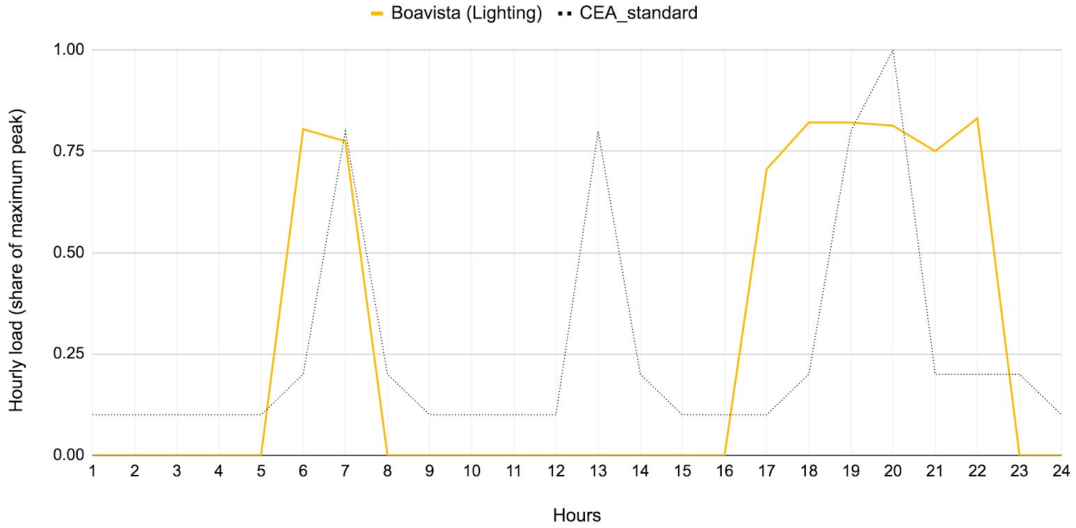


Figure 20: Reference usage profile of lighting (red) for Boavista (proportional to the neighbourhood's occupancy rate), expressed as a fraction of the maximum fictional peak, compared with the reference profile proposed by CEA (black)

As an additional constraint, the sum of the average annual demand for appliances, lighting and heating was calculated, providing the expected electricity demand of a reference household of 3.5 residents under all the assumptions priorly made. For each neighbourhood, the average electricity demand per capita (Figure 21) and per square meter (Figure 22) were then calculated and compared to the portuguese references.

As summarized in Equation (4) the portuguese average specific electricity demand $(EL_{y,pm2} = 25\ \frac{kWh}{y\cdot m2})$ was calculated multiplying the per capita reference value per the average number of people by conventional dwelling ($\delta = 1.6\ \frac{p}{dw.}$ in 2019) (PortData, 2020b) and dividing it by the average dwelling size $(A_{dw} = 78.2\ \frac{m2}{dw.})$, both these values refer to Lisbon municipality.

$$EL_{y,pm2} = 25\ \frac{kWh}{y\cdot m2} = \frac{EL_{y,pc}\cdot\delta}{A_{dw}} = \frac{(1{,}219.6\ \frac{kWh}{y\cdot p})\cdot(1.6\ \frac{p}{dw.})}{(78.2\ \frac{m2}{dw.})} \tag{4}$$

While Figure 21 indicates that, so far, the assumptions made were consistent with the actual consumption patterns, Figure 22 shows the expected impact of living conditions (basically small, highly occupied apartments) on energy efficiency measurements.

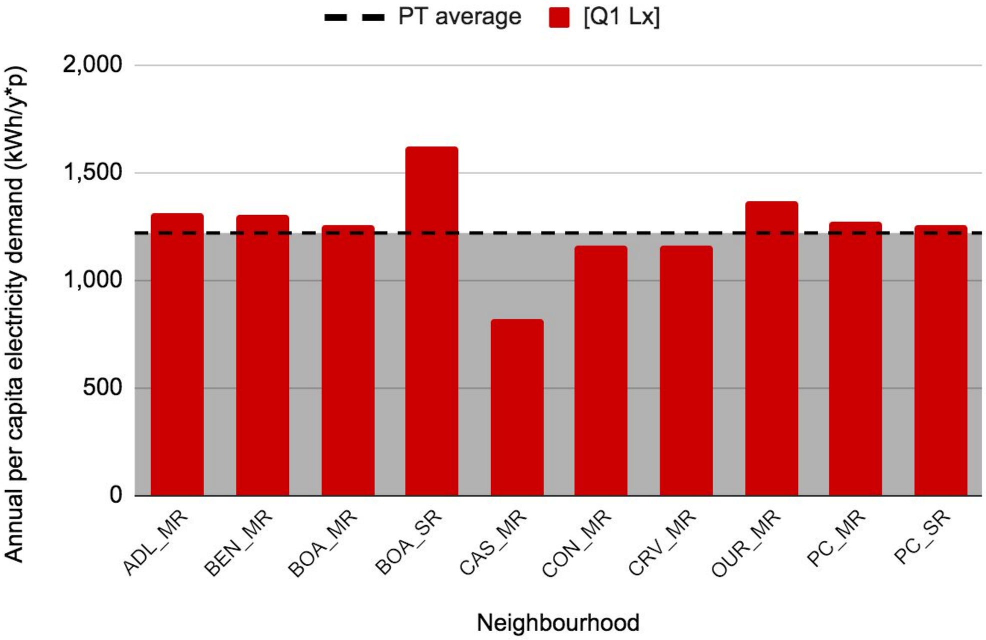


Figure 21: Expected electricity demand per capita of a reference household of 3.5 residents for each neighborhood in the case study (red), compared with the Portuguese average (black)

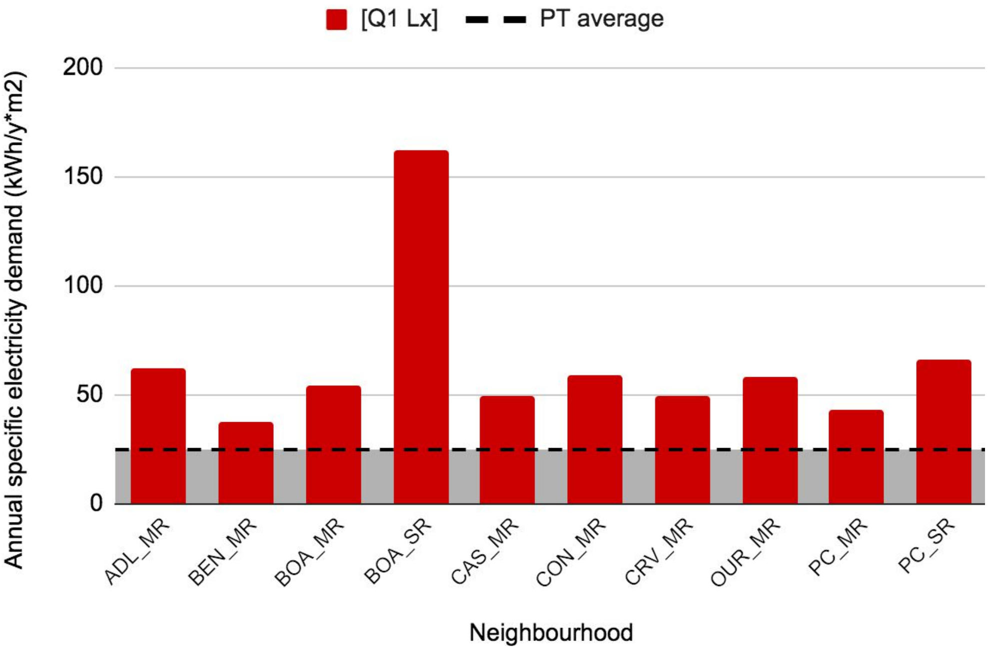


Figure 22: Expected electricity demand per square meter of a reference household of 3.5 residents for each neighborhood in the case study (red), compared with the Portuguese average (black)

3.5 Energy performance simulation (City Energy Analyst)

City Energy Analyst is an open-source software tool for the analysis and the optimization of urban energy systems. For the purpose of this thesis, CEA enables to simulate the energy performance of entire neighbourhoods with little inputs, such as: geometry, construction standards and schedules. However, CEA is very sensitive to the data organization, which has to be named correctly and organized into specific folders following the structure illustrated in Annex IV.

Once the shapefiles (*zone.shp* and *surroundings.shp*) were ready, a project could be started in CEA. Thus, accessing the “Database Editor” window, all the components needed to describe the construction standards were added to the folder “Assemblies”, which is structured in the following sub-folders:

- **Envelope**: catalogue of reference envelope elements (window, roof, wall, floor, etc.) and their main thermal properties (transmittance, emissivity, embodied emissions, etc.); filled with the elements and U-values found in Table 5;
- **HVAC**: catalogue of reference HVAC systems (for heating, cooling, DHW, etc.) and their main operational parameters (supply temperature, heat flow, etc.); the type of heating system chosen was either “None”, for those buildings buildings assumed to lack heating, or “Radiator (90/70)”, for all the rest (despite the choice does not represent the reality of many households in Portugal, which tend to use autonomous electric heaters); CEA standard values were used for cooling (“None”) and DHW (“High temperature water (60/10)”);

- **Supply**: catalogue of reference supply systems (for heating, cooling, DHW, etc.) and their main operational parameters (feedstock type, efficiency, useful-life years, etc.); the type of heating supply system chosen was either "None" or "Electric heater", which was defined as grid electricity supply with 100% efficiency; the type of DHW supply system chosen was "natural gas-fired boiler";

Hence, the assemblies just defined were incorporated into the "Construction Standards" defined by CEA (which referred to Switzerland), according to the Lisbon archetypes described in chapter 3.2. The resulting database was exported to a backup folder, becoming the "technology" folder of all CEA projects.

Similarly, the occupation density (*Occ_m2pax*) and the appliances and lighting peak loads (*Ea_Wm2* and *El_Wm2*), as well as the occupancy, heating, appliances and lighting schedules defined in chapter 3.4 were incorporated into the residential "Use-types" predefined by CEA. Table 7 presents the variation of these parameters within the case study neighbourhoods, comparing the values with the standard developed by CEA for Switzerland (CH).

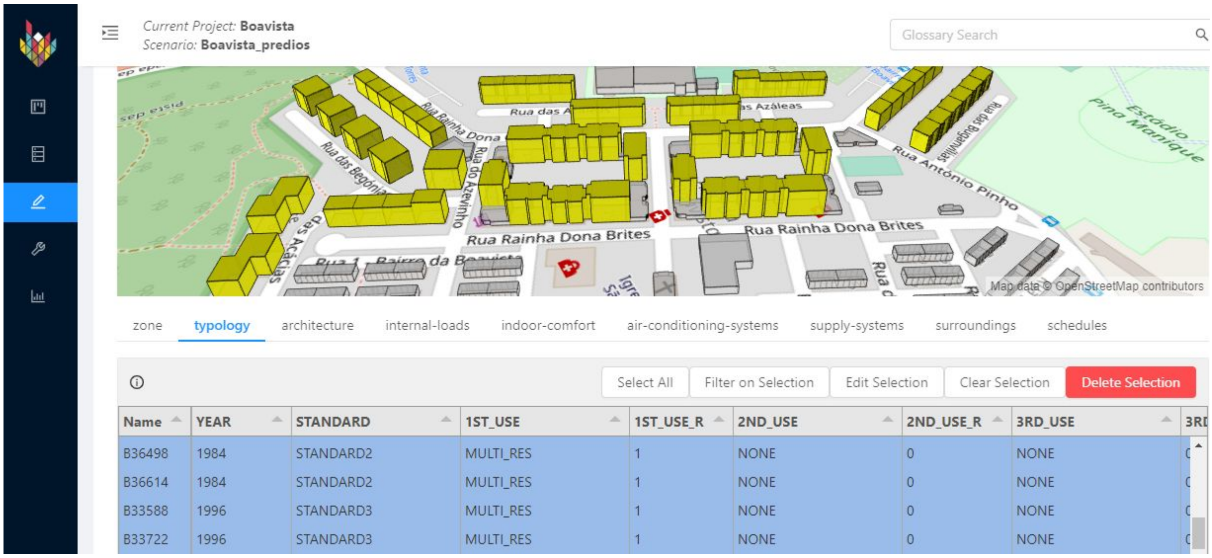
Other variables were kept unaltered, in particular the peak sensible heat load of people $(Qs\_Wpax = 70 \frac{W}{p})$, the moisture released by occupancy $(X\_ghpax = 80 \frac{g}{p \cdot h})$, the daily DHW $(Vww\_lpdpax = 35 \frac{l}{p \cdot d})$ and fresh water consumption $(Vw\_lpdpax = 140 \frac{l}{p \cdot d})$ and the schedules' monthly multiplier (0.8 for all months), which accounts for the monthly variations in the occupancy rate (e.g. summer holidays).

Table 7: Variation of occupation density (*Occ_m2pax*), appliances peak load (*Ea_Wm2*) and lighting peak load (*El_Wm2*) within the neighbourhoods of the case study, compared with the standard values developed by CEA for Switzerland (CH)

INTERNAL_LOADS	CH	ADL_MR	BOA_SR	BOA_MR	BEN_MR	CAS_MR	CON_MR	CRV_MR	OUR_MR	PC_SR	PC_MR
Occupancy density **Occ_m2pax** (m^2/p.)	**50**	16.2	12.6	18.9	26.7	12.7	15.0	17.9	17.9	14.6	22.4
Peak load appliances **Ea_Wm2** (W/m^2)	**8**	12.0	32.0	10.0	7.0	10.0	10.0	9.0	10.0	13.0	9.0
Peak load lighting **El_Wm2** (W/m^2)	**2.7**	5.0	13.0	4.0	3.0	4.0	5.0	4.0	4.5	6.0	3.5

Thereby, the typology database in the "Input Editor" window was filled by assigning to each building its standard and main-use, which were identified as explained in chapter 3.6.2; Figure 23 shows an example of the "Input Editor" working environment for the 59 buildings simulated in Bairro do Boavista.

The "Archetypes Mapper" tool thus assigned to each building the construction parameters relative to its standard. The "Terrain Helper" and the "Climate Helper" were used respectively to define the topography of the neighbourhood and to import the local weather data, obtained for the period 2004-2018 from EnergyPlus (EnergyPlus, 2020).



Current Project: **Boavista**
Scenario: **Boavista_predios**

Name	YEAR	STANDARD	1ST_USE	1ST_USE_R	2ND_USE	2ND_USE_R	3RD_USE
B36498	1984	STANDARD2	MULTI_RES	1	NONE	0	NONE
B36614	1984	STANDARD2	MULTI_RES	1	NONE	0	NONE
B33588	1996	STANDARD3	MULTI_RES	1	NONE	0	NONE
B33722	1996	STANDARD3	MULTI_RES	1	NONE	0	NONE

Figure 23: Screenshot of the "Input Editor" interface of CEA for the 59 buildings simulated in Boavista

At this point, the "Demand forecasting" tools could finally be used. First, "Building Solar Radiation" was run to simulate the heat and light gains obtained by each building due to solar radiation. Then, "Schedule Maker" defined precisely the schedules for each building according to the main use. Finally, "Building Energy demand" simulated the energy consumption and thermal performance. The outputs of each simulation were included in "Total_demand.csv", a breakdown of energy and power loads by final use and by source of supply, and in several individual building files named as the ID code assigned to each building (e.g. "B44133.csv"), presenting the internal loads and the indoor and outdoor temperatures for every hour of the year.

Because of the COVID-19 confinement the laboratory could not be used for the simulations, so a much less performing personal device had to be used to run the simulations. Due to computing processing constraints, the maximum size of the zone which could be simulated at once was around 50 buildings. Neighbourhoods like Condado, Padre Cruz or Boavista had to be split into smaller areas, which together still represented the main constructive solutions found in those neighbourhoods.

3.6 Index of Vulnerable Homes

Castaño-Rosa et al. (2020a) developed a novel index of vulnerable homes in terms of fuel poverty obtained by a combination of different existing fuel poverty indicators together with the energy efficiency of buildings. Three dimensions are included in the IVH: monetary poverty, energy and thermal comfort. Different levels of vulnerability are thus defined and linked to the health-related quality of life of the households. The IVH was originally developed for Spain, this study thus adjusts the index to the Portuguese context.

Finally, the dimension indicators proposed by Castaño-Rosa et al. (2020a) were adapted to the data available to this study; this simplification may have sacrificed rigour in favor of attainability.

3.1.1 Energy Indicator (EnI)

The overall grid electricity consumption (ED), which includes lighting, appliances and heating, was the feature used to assess buildings' energy performance as compared to each other and to statistical data. The Energy Indicator (*EnI*) is calculated usingEquation (5):

$$EnI = \frac{EL}{AEC} \tag{5}$$

where EL is the simulated electricity consumption required, while AEC is the average per capita domestic electricity consumption of a Portuguese citizen, which was $1,220 \frac{kWh}{y \cdot p}$ in 2017 (PortData, 2020a). Therefore, housing energy consumption is considered inadequate or "inadmissible" if it is above the energy threshold (EnI>1). Moreover, the EnI of those buildings lacking a heating system is automatically labeled as "inadmissible", since their electricity consumption is excessively low $(700 \frac{kWh}{y \cdot p})$ to satisfy the residents' needs. Else, buildings equipped with heating showing a EnI below 1 are considered "admissible".

It has to be noted how the EnI as defined here differs drastically from the original proposal of Castaño-Rosa et al. (2020a), since they obtained EC from simulations in which systems are correctly and fully used and use median energy consumption (MEC) as a threshold instead of AEC.

3.1.2 Thermal comfort Indicator (CI)

The CI only accounts for thermal comfort, factors like light and acoustics remain outside the scope of this study. The evaluation of thermal comfort derives from the application of the adaptive model ASHRAE 55–2010 (ASHRAE, 2010) together with the normative EN 15251:2007 (CEN, 2007). The model defines a temperature range of comfort based on the mean external temperature of the previous week, if the internal temperature fell into the band then the household is in a situation of comfort. Those households with a high number of hours outside the comfort range are said to be in a vulnerable situation. "Admissible" comfort conditions were defined as for the average daily temperature to be within the band 80% of the time or more. A daily accounting was preferred since an hourly one would have required a higher computational cost while offering similar results. The threshold of 80% means that members of these households may be thermally uncomfortable for 5 hours per day, and these hours are considered during sleeping hours.

3.1.3 Monetary Poverty Indicator (MPI)

Two poverty lines were proposed by Castaño-Rosa et al. (2020a): a monetary poverty threshold (MPT) and a severe monetary poverty threshold (SMPT). The MPT represents the condition of living with a low income, which is set to 60% of the median equivalised disposable income after social transfers, this value equals in Portugal 5,607€ per person per year (467€ per month) (INE, 2019a). The SMPT represents a more precarious level of poverty, which is set by the social benefit granted by the government to families in social exclusion, which in Portugal cannot earn more than 189.66€ per person per month(Segurança social, 2019). To obtain a MPT and SMPT valid for each household, both values had to be multiplied by the equivalent household size (Uc), which is calculated using Equation (6).

$$U_c = (1 + 0.5 \cdot (A - 1) + 0.3 \cdot B) = (1 + 0.5 \cdot (A - 1) + 0.3 \cdot (A \cdot b_{neigh})) \quad (6)$$

where A is the number of adults and B the number of minors per family unit, while b_{neigh} is the share of minors living in each neighbourhood.

Both indicators are thus calculated dividing the household’s net income (*NI*) by the respective poverty threshold (*T*: which stands for MPT or *SMPT*), as shown inEquation (7).

$$MPI = \frac{NI}{T} = \frac{I - (HE + EE)}{T} \quad (7)$$

where I is the household income, *HE* is the housing expenditure (monthly rent) and *EE* is the energy expenditure which derives from the simulation. A household is said to be in a situation of monetary poverty or severe monetary poverty if its net incomes fall below the respective threshold (*MPI* < 1).

3.7 Quality-Adjusted Life-Years and Health-Related Quality-of-Life Cost

Castaño-Rosa et al. (2020a) identified 13 levels of vulnerability derived from the different combination of the three indicators just presented. Each of these levels was given a specific score on a five-level European Quality of Life 5 Dimensions’ questionnaire (EQ-5D-5L), a standard measure developed by the EuroQol Group to provide a simple and generic measure of health status for clinical and economic appraisal (EuroQol Group, 1990). A score from 1 to 5, from best to worst, was assigned to five health dimensions (Mobility, Self-care, Usual activities, Pain/Discomfort and Anxiety/Depression) according to the vulnerability level obtained. A value of quality-adjusted life-years (QALYs) could then be bound to the EQ-5D-5L scores, using a set of coefficients specific for Portugal population (Ferreira et al., 2019). A $QALY$ equal to 1 represents the best possible life condition, while values below 0 represent that the demeaning living conditions might cause the death of a household member. Finally, a monetary value portraying the NHS expenses related to the different QALYs was determined using the Health-related Quality-life Cost ($HRQLC$) (Threlfall, 2011). The $HRQLC$ is a measure of the cost-effectiveness value of a human life, which represents what amount of money the NHS would have to pay to keep a person alive in perfect health for one year. The reference measure of this parameter for Portugal ($HRQLC_{ref,\,PT}$) is set by the NHS to 20,000€. The $HRQLC$ of each IVH level was thus calculated usingEquation (8).

$$HRQLC = (1 - QALY) \cdot HRQLC_{ref,\,PT} \tag{8}$$

It must be noted that the $HRQLC$ would represent the annual NHS monetary expenses only if all citizens lived in perfect health conditions, a situation which is far from true. The $HRQLC$ savings caused by retrofit actions can be shown next to the retrofit cost, however, since they do not portray actual savings for the NHS and, to be consistent, should not be used to calculate NPV and ROI. Therefore, diverging from Castaño-Rosa et al. (2020a), this study proposes an alternative methodology to estimate pragmatic NHS savings which could be representative of the actual NHS status and comparable with retrofit costs.

The pragmatic method starts by defining an average $QALY$ for Portugal ($QALY_{avg,\,PT}$ = 0.524), which is calculated as the average of the $QALYs$ conferred to each IVH level. Hence, the average QALY is linked to the current expenditure on healthcare per capita ($NHS\_cost_{avg,\,PT}$), which in Portugal are equal to 1,784.8€ per year. A new reference value for NHS cost ($NHS\_cost_{ref,\,PT}$), associated with a null QALY, is then defined usingEquation (9).

$$NHS\_cost_{ref,\,PT} = \frac{NHS\_cost_{avg,\,PT}}{(1 - QALY_{avg,\,PT})} = 3,748\frac{€}{y} \tag{9}$$

Finally, the NHS_cost related to each IVH level is calculated usingEquation (8) after replacing $HRQLC_{ref,\,PT}$ with the $NHS\_cost_{ref,\,PT}$ just calculated. Table 8 presents the 13 IVH levels defined by Castaño-Rosa et al. (2020a) and the respective values introduced in this chapter.

Table 8: Definition of the 13 IVH levels and the corresponding answers to the questionnaire on quality of life (EQ-5D-5L), through the combination of the three-dimension indicators (Monetary poverty, Energy and Comfort - from Castaño-Rosa et al. (2020a)); shown together with the calculated Quality-Adjusted Life-Years (QALY - from Ferreira et al. (2019)), Health-Related Quality-of-Life Cost (HRQLC - from Castaño-Rosa et al. (2020a)) and NHS_cost (author's contribution) adapted to the Portuguese context

IVH	Monetary poverty	Energy	Comfort	EQ-5D-5L	QALY	HRQLC	NHS_cost
1	No Monetary Poverty	Admissible	Inadmissible	11121	0.959	820€	154€
2	No Monetary Poverty	Inadmissible	Admissible	11122	0.899	2,020€	379€
3	No Monetary Poverty	Inadmissible	Inadmissible	11133	0.814	3,720€	697€
4	Monetary Poverty	Admissible	Admissible	11223	0.830	3,400€	637€
5	Monetary Poverty	Admissible	Inadmissible	11333	0.751	4,980€	933€
6	Severe Monetary Poverty	Admissible	Admissible	12333	0.703	5,940€	1,113€
7	Monetary Poverty	Inadmissible	Admissible	13333	0.681	6,380€	1,196€
8	Monetary Poverty	Inadmissible	Inadmissible	13433	0.609	7,820€	1,466€
9	Severe Monetary Poverty	Admissible	Inadmissible	14334	0.468	10,640€	1,994€
10	Severe Monetary Poverty	Inadmissible	Admissible	13344	0.401	11,980€	2,245€
11	Severe Monetary Poverty	Inadmissible	Inadmissible	14455	0.019	19,620€	3,677€
12	Monetary Poverty	Inadmissible*	Inadmissible	24455	-0.029	20,580€	3,857€
13	Severe Monetary Poverty	Inadmissible*	Inadmissible	25555	-0.295	25,900€	4,854€

*Represented by households who cannot afford minimum energy consumption due to a lack of monetary resources.

3.8 Economic analysis

The benefits of the retrofits scenarios were evaluated in economic terms, including the health gains embodied in the *HRQLC* index (see chapter 2.3.4). The costs of retrofit (CR) were calculated using standard maximum unit costs for the retrofit options and reference useful life years (Y) suggested by the POSEUR program (POSEUR, 2016). The Net Present Value (*NPV*) and the Return on Investment (*ROI*) were calculated (using a discount rate (*DR*) equal to 3% (Steinbach and Staniaszek, 2015)) for each retrofit scenario under four conditions, which reflect the peculiarity of the case study.

Public housing residents in Portugal pay a reduced social tariff for electricity, which in turn shrinks the margin of monetary savings in the electricity bill. The first condition examines if the modest savings obtained with the social tariff ($S_{el,\ social}$) would be enough to appropriately cover the cost of retrofit.

Rather, the second condition wonders what would be the outcome if, instead of being publicly owned, the same building was part of the housing market and its residents had to pay regular electricity tariffs. For this comparison, from the same electricity consumption, the extent of each building's annual bill was calculated using both tariffs.

Under the third condition, the cost of retrofit would be repaid not only by the savings obtained with the social tariff but also by the annual NHS savings, calculated multiplying the *HRQLC* variation after the retrofits by the number of households in the respective buildings (N_{hh}), as proposed by Castaño-Rosa et al. (2020a).

Lastly, the fourth condition maintains the same logic as the third, but it uses the pragmatic methodology proposed in the previous chapter, which replaces *HRQLC* with *NHS_cost*. The *NPV* and the *ROI* of each retrofit activity *i* were calculated by usingEquation (10) andEquation (11).

$$NPV_i = \left(\sum_{t=1}^{Y} \frac{1}{(1+DR)^t}\right) \cdot [S_{el.,\,social} + (\Delta(NHS\_cost) \cdot N_{hh})] - C_{R,\,i} \tag{10}$$

$$ROI_i = \frac{C_{R,\,i}}{S_{el.,\,social} + (\Delta(NHS\_cost) \cdot N_{hh})} \tag{11}$$

where: Y is the useful life years (25 for Windows and EPBD; 35 for Wall); DR is the discount rate, considered equal to 3%; $S_{el.,\,social}$ is are the savings obtained in the subsidized energy bills; NHS_cost is the public healthcare expenses of each household; N_{hh} is the number of households $C_{R,\,i}$ is the cost of retrofit i for each building.

The methodology proposed in this thesis results in various implications for the design of local energy policies, enabling public authorities to successfully evaluate economic, social and environmental considerations at once. In particular, this methodology allows to quantify in monetary terms the intangible benefits of building retrofitting, such as improving comfort and health, and include them in the decision processes. This results in a paradigm shift of the investment in public housing retrofitting, which moves from being seen as a public cost to a social benefit, responding to the ultimate goal of public policies to ensure welfare.

4. Results and Discussion

The results of this thesis are divided into three parts, resulting from the application of the methodological steps presented in section 2, as follows: Energy performance (see chapter 2.3.1), thermal comfort and economic analysis. To conclude the section, a reflection on the implication of the results on the implementation of local energy policy will be proposed.

The results of the analysis made on the oldest buildings of Boavista and Padre Cruz, which are planned to be demolished and reconstructed, are presented separately from the rest.

4.1 Energy performance

From the urban building simulations, the energy performance of 340 buildings in the study area was evaluated in terms of annual end-use energy demand (ED), grid electricity (EL) and natural gas (NG) consumption. The implementation of passive retrofit measures did not affect the NG demand, which covers domestic hot water production, the trend of this term will therefore be neglected further on.

The analysis of the results compares the implementation of individual retrofit measures (windows replacement (WINDOWS) and implementation of thermal insulation on exterior walls (WALLS)) to the renovation of the entire building envelope (EPBD) for the different neighbourhoods.

At the current status (BASE) the average end-use energy demand is equal to $75.4\ \frac{kWh}{y \cdot m^2}$, while the grid electricity demand to $42.3\ \frac{kWh}{y \cdot m^2}$ As shown in Figure 24, the lower energy demand is found onAlfredo Bensaúde, with an average ED equal to $57.3\ \frac{kWh}{y \cdot m^2}\ \left(EL = 33.3\ \frac{kWh}{y \cdot m^2}\right)$, while the higher ED refers to Casalinho da Ajuda, with an annual demand of $101.0\ \frac{kWh}{y \cdot m^2}\ \left(EL = 56.9\ \frac{kWh}{y \cdot m^2}\right)$.

Figure 25 repeats the analysis for the oldest buildings of Boavista and Padre Cruz, which belong to standard 1. The current average electricity consumption for both cases is around $72 - 73\ \frac{kWh}{y \cdot m^2}$ (yellow), which is much higher than even the highest value measured before. Curiously, the effect of the reconstruction is very different for the two neighbourhoods: the project proposed for Padre Cruz reaches around 65% of electricity savings, while the Boavista one has almost no benefit (4% savings).

Assumptions had to be made to complement the information retrieved from the project datasheets, these results are probably due to incorrect assumptions made for the Boavista project, since it would be truly surprising for such a project to not implement energy savings. For this reason, the results obtained for the buildings affected by these assumptions will be excluded further on.

The end-use energy demand of the oldest buildings (Standard 2) is on average $93.4\ \frac{kWh}{y \cdot m^2}$ $\left(EL = 54.5\ \frac{kWh}{y \cdot m^2} - Figure\ 26\right)$, while that of the most modern ones (Standard 5) is $71.0\ \frac{kWh}{y \cdot m^2}\ \left(EL = 36.7\ \frac{kWh}{y \cdot m^2}\right)$.

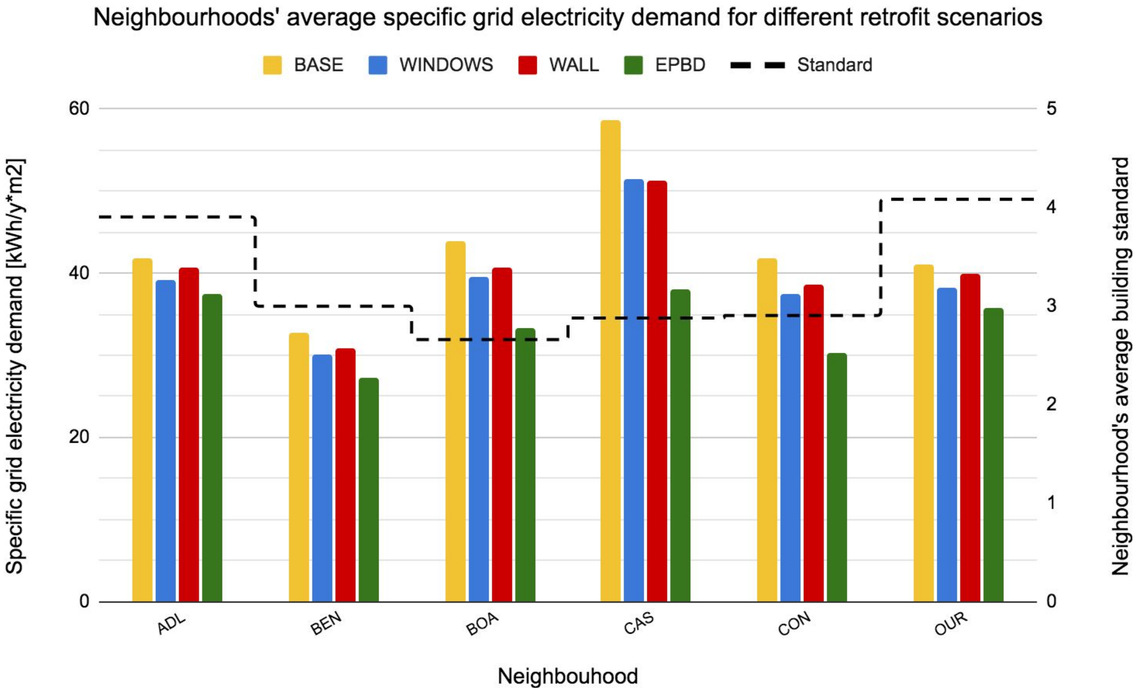


Figure 24: Average specific electricity demand (EL) and average construction standard (black dashed line) of the buildings of each neighbourhood, at the current situation (BASE - yellow) and after the implementation of the retrofit measures WINDOWS (blue), WALL (red) and EPBD (green)

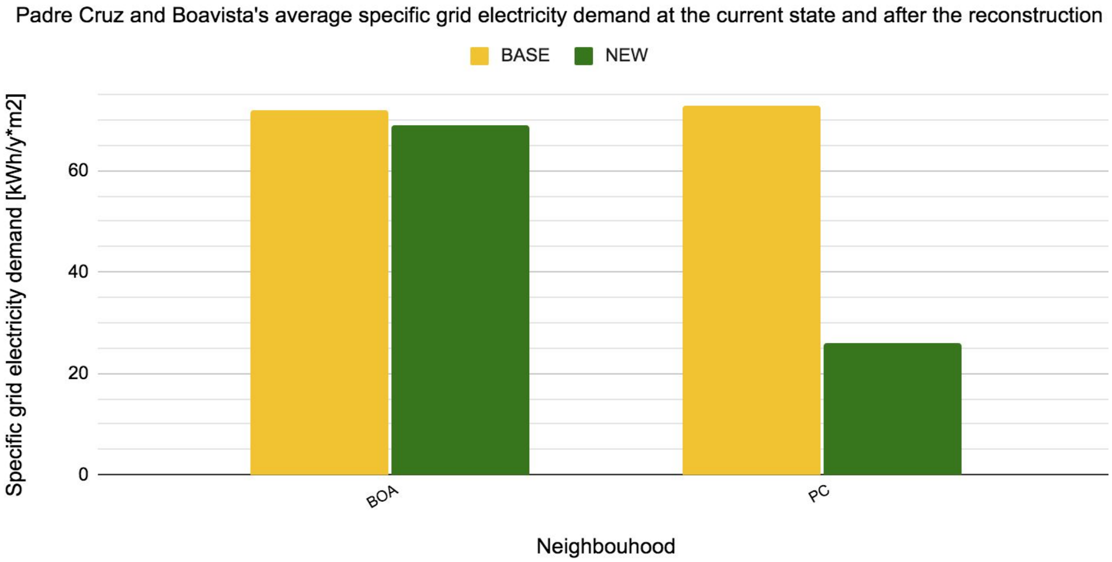


Figure 25: Average specific electricity demand (EL) of the oldest buildings of Boavista and Padre Cruz, at the current situation (BASE - yellow) and after the reconstruction planned by the *Eco-Bairros* (green)

As shown in Figure 27, when accounting by per capita consumption an opposite situation is revealed. Indeed, the per capita end-use consumption of buildings of standard 2 is on average $1,545\ \frac{kWh}{y \cdot p}$ $(EL = 913.8\ \frac{kWh}{y \cdot p})$, while that of other standards ranges between 2,014 and $2,424\ \frac{kWh}{y \cdot p}$ $(EL = 1,200\ \&\ 1,471\ \frac{kWh}{y \cdot p})$.

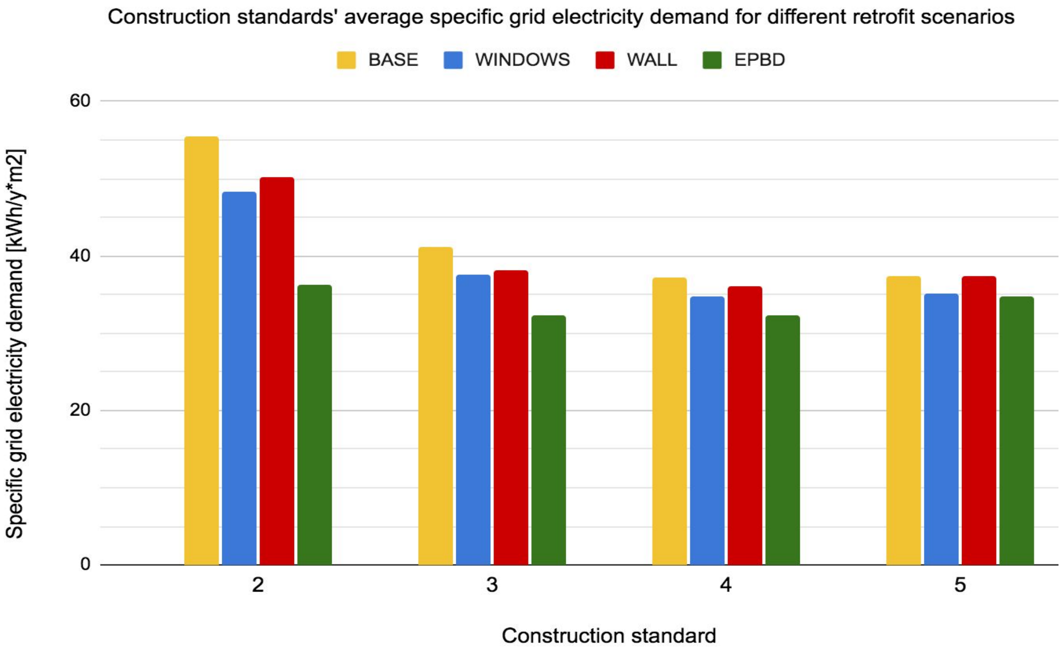


Figure 26: Average specific electricity demand (EL) of the buildings belonging to the same construction standard, at the current situation (BASE - yellow) and after the implementation of the retrofit activities WINDOWS (blue), WALL (red) and EPBD (green)

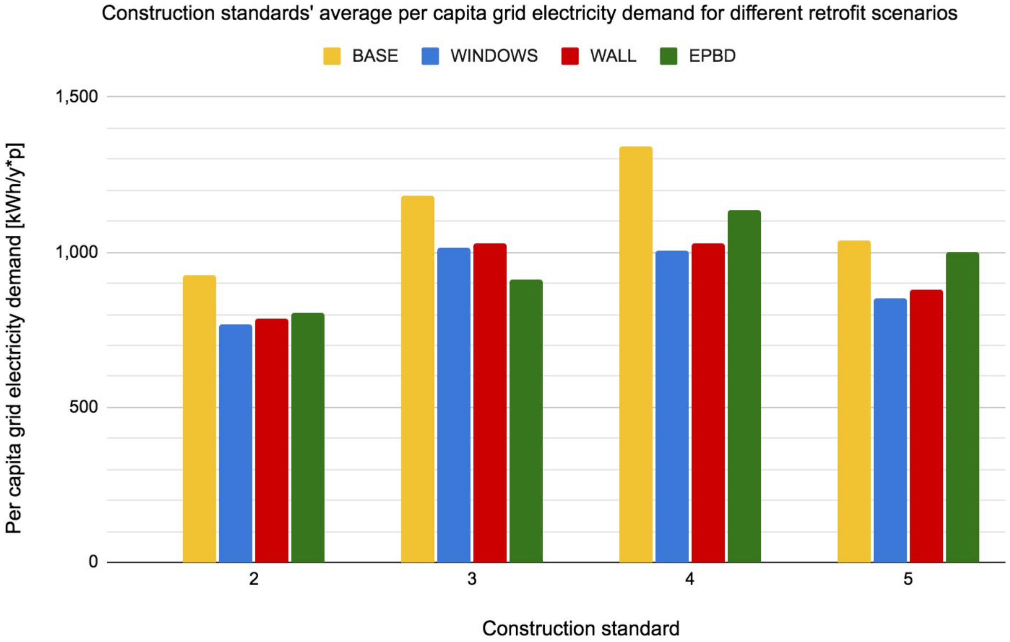


Figure 27: Average per capita electricity demand (EL) of the buildings belonging to the same construction standard, at the current situation (BASE - yellow) and after the implementation of the retrofit activities WINDOWS (blue), WALL (red) and EPBD (green)

The discrepancies between specific and per capita consumption accounting can be exposed by comparing Figure 28 and Figure 29. In fact, while the specific energy consumption is inversely proportional to the area occupied by the building (Figure 28), the per capita energy consumption is independent from the building's number of residents (Figure 29).

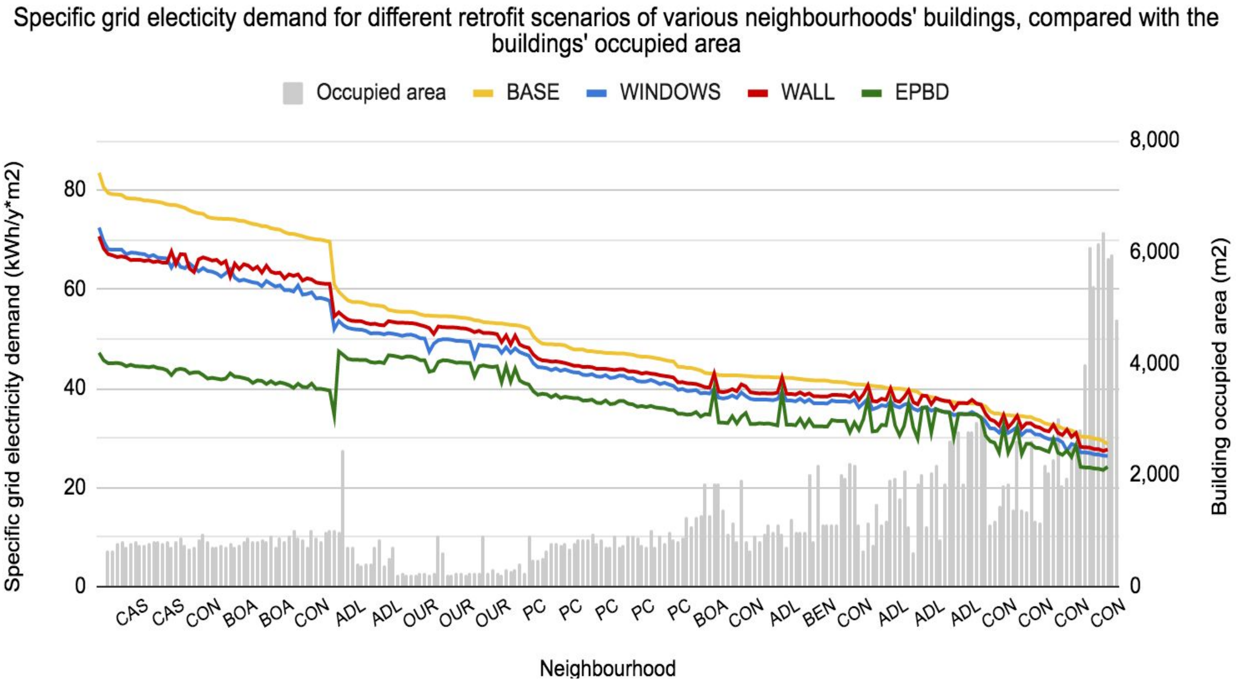


Figure 28: Specific grid electricity demand (EL) of the 224 buildings simulated equipped with a heating system, organized in descending order, at the current situation (BASE - yellow) and after the implementation of the retrofit activities WINDOWS (blue), WALL (red) and EPBD (green), compared to the occupied area of the buildings (grey)

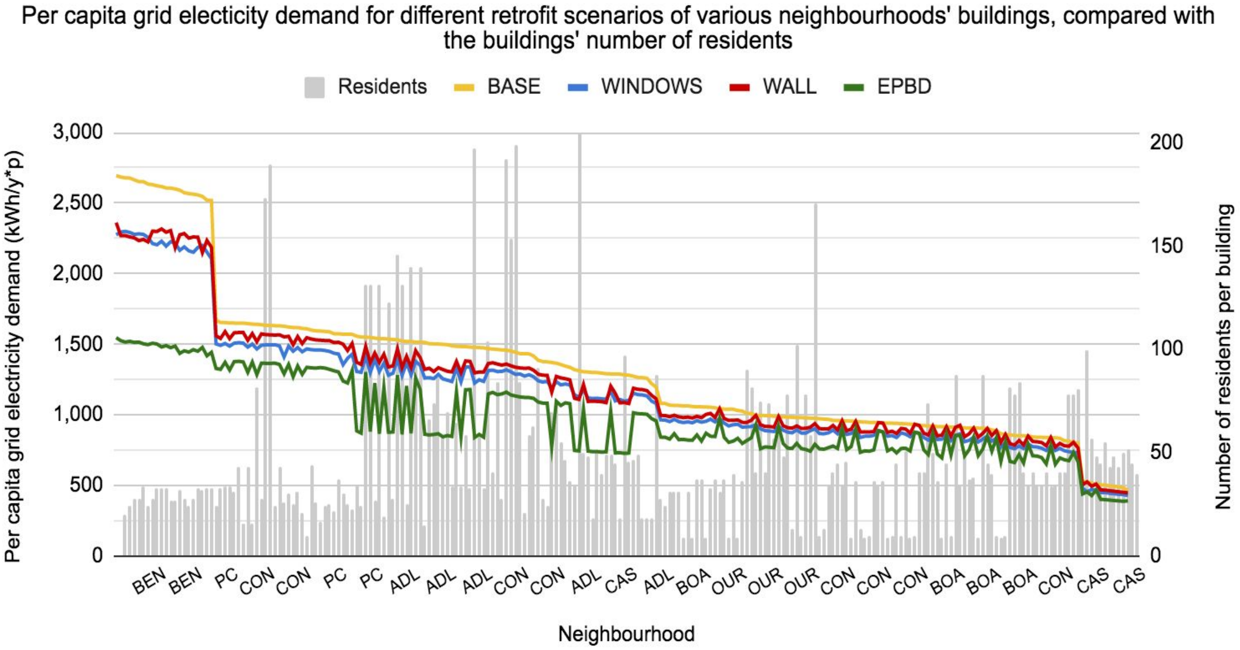


Figure 29: Per capita grid electricity demand (EL) of the 224 buildings simulated equipped with a heating system, organized in descending order, at the current situation (BASE - yellow) and after the implementation of the retrofit activities WINDOWS (blue), WALL (red) and EPBD (green), compared to the number of residents of the buildings (grey)

These results highlight that EPCs are useful to compare residential energy performance for different constructive solutions and systems in standardized conditions, but they do not reflect the differences in the occupation of each building. Under these conditions, people living in big efficient dwellings (usually a wealthy fraction of the population) may end up consuming more than some living in inefficient yet small homes without being accounted for their overconsumption.

Figure 30 shows the electricity consumption pattern for the baseline (yellow) and the three retrofit scenarios (blue, red and green) of all the buildings simulated, while also specifying to which standard (grey) those EL values refer. All the figures shown in this chapter reveal how the EPBD retrofit would reduce the current inequality of energy performance within the different neighbourhoods.

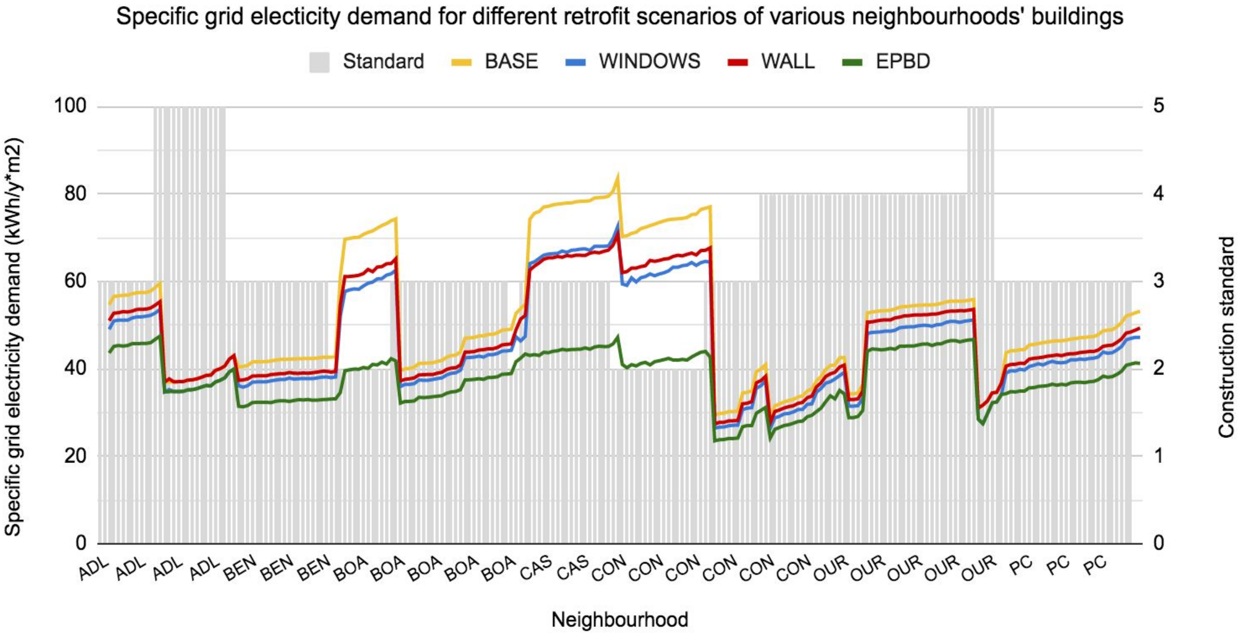


Figure 30: Distribution of the specific grid electricity demand (EL) of the 224 buildings simulated equipped with a heating system, at the current situation (BASE - yellow) and after the implementation of the retrofit activities WINDOWS (blue), WALL (red) and EPBD (green); the buildings are organized in ascending order of their standard (grey) within the same neighbourhoods

The average end-use energy savings are 4,4% for Windows retrofit, 3.0% for Wall and 10.0% for EPBD; regarding electricity consumption, the savings increase to 7.1%, 4.8% and 16.2% respectively.

The highest savings are reached by 55 buildings (16%) of standard 2 and 3 located in thee neighbourhoods (Boavista, Condado and Casalinho da Ajuda), which show EL savings of more than 40% for EPBD (ED savings >20%) and than 10% for Windows and Wall. Those buildings can be easily identified in Figure 31, which shows the electricity savings coming with the three retrofit scenarios (blue, red and green) and the construction standard (grey) to which they refer. For the sake of clarity, the 116 buildings assumed to have no heating were not shown in Figure 30 and Figure 31 since their consumption did not change with the retrofits.

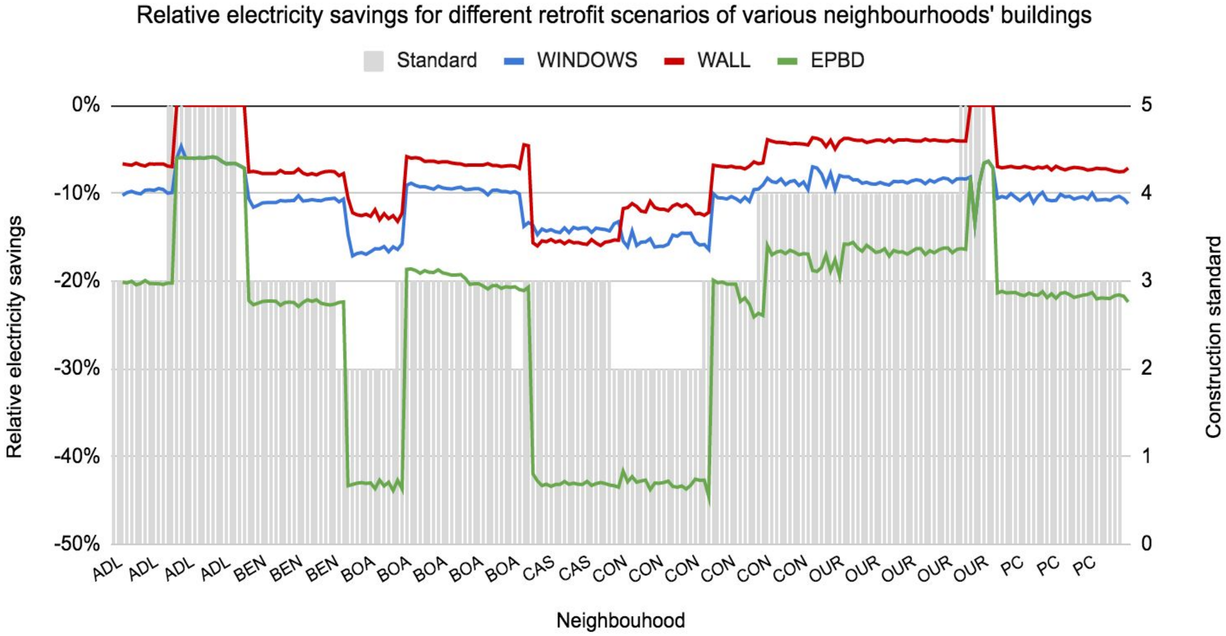


Figure 31: Grid electricity savings of the 224 buildings simulated equipped with a heating system, after the implementation of the retrofit activities WINDOWS (blue), WALL (red) and EPBD (green); the buildings are organized in ascending order of the baseline (BASE) specific grid electricity demand (EL) within the same construction standard (grey)

Finally, as an example, figure 32 shows the current spatial distribution of specific electricity consumption in Condado (Baseline) and its evolution after the implementation of the three retrofit measures proposed. The buildings in red on the right band of the first figure are the oldest and less efficient (identified by standard 2) and are clearly the most affected by the renovation, since their EL passed from more than $75 \frac{kWh}{y \cdot m^2}$ to less than $45 \frac{kWh}{y \cdot m^2}$ after the EPBD retrofit. Also, the buildings consuming less $(EL < 20 \frac{kWh}{y \cdot m^2})$ are the ones without a heating system, which are marked by diagonal dashed lines.

The databases collecting information on the distribution of the energy consumption in each neighbourhood are available in Annex E, in order to be accessed using QGIS.

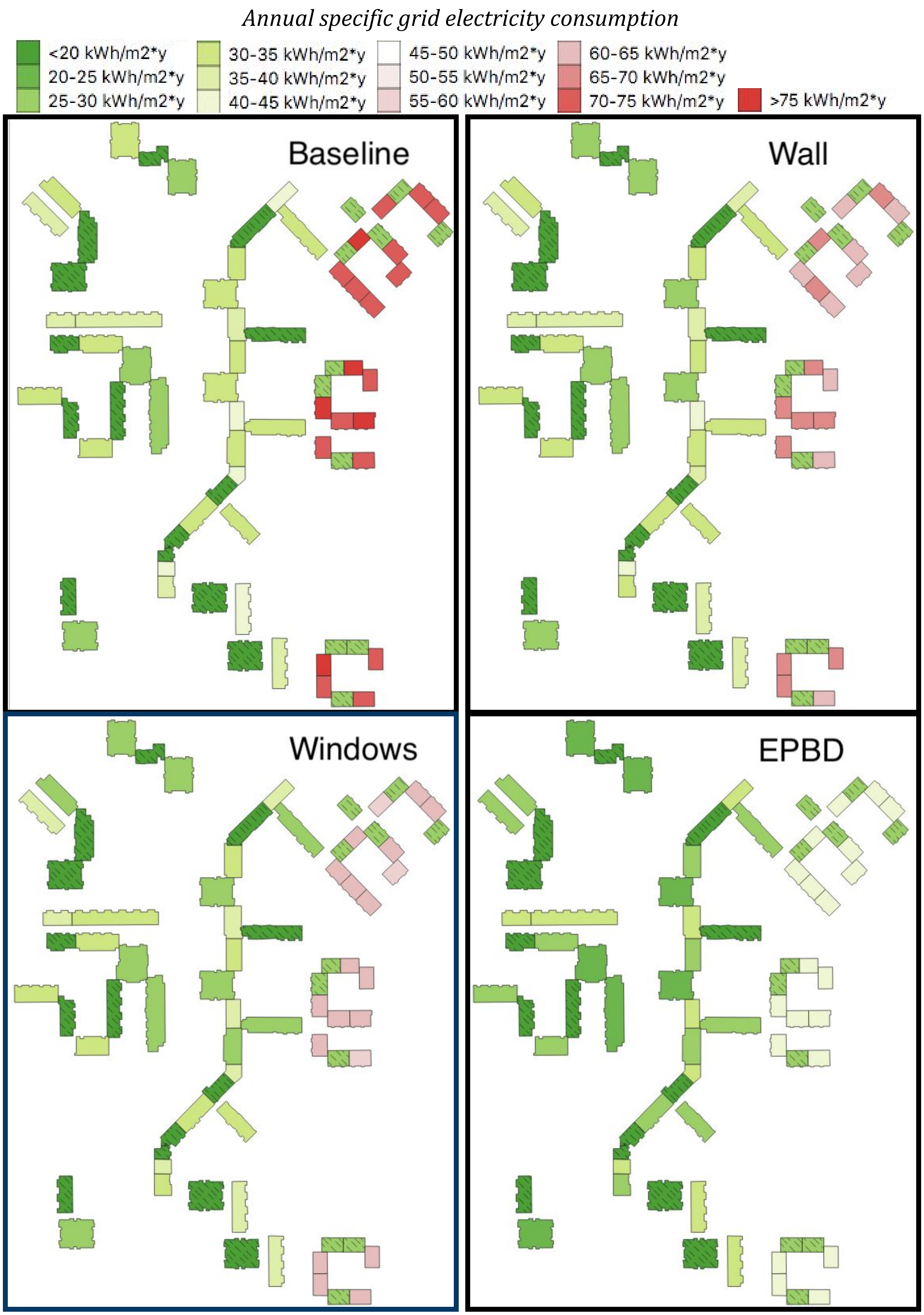


Figure 32: Spatial distribution of specific grid electricity consumption (EL - $\frac{kWh}{y\cdot m^2}$) in Condado, at the current state (Baseline - top left) and after the implementation of the Wall (top right), Windows (bottom left) and EPBD (bottom right) retrofits; the buildings considered lacking a heating system are marked by diagonal dashed lines

4.2 Thermal comfort

As shown in Figure 34, all retrofit scenarios reduce the hours of thermal discomfort related to cold occurrences suffered along the year by each neighbourhood's residents. EPBD retrofit is the one contributing the most to improve comfort conditions, often leading to overtake the threshold of 80% of hours in comfort conditions (Figure 33). The only neighbourhood damaged by the intervention is Alta de Lisboa, which is the one presenting the most modern buildings (30% of standard 5). This is due to the overheating effect caused by the additional insulation, which is strongest in the newer buildings, as it can be deduced by Figure 35.

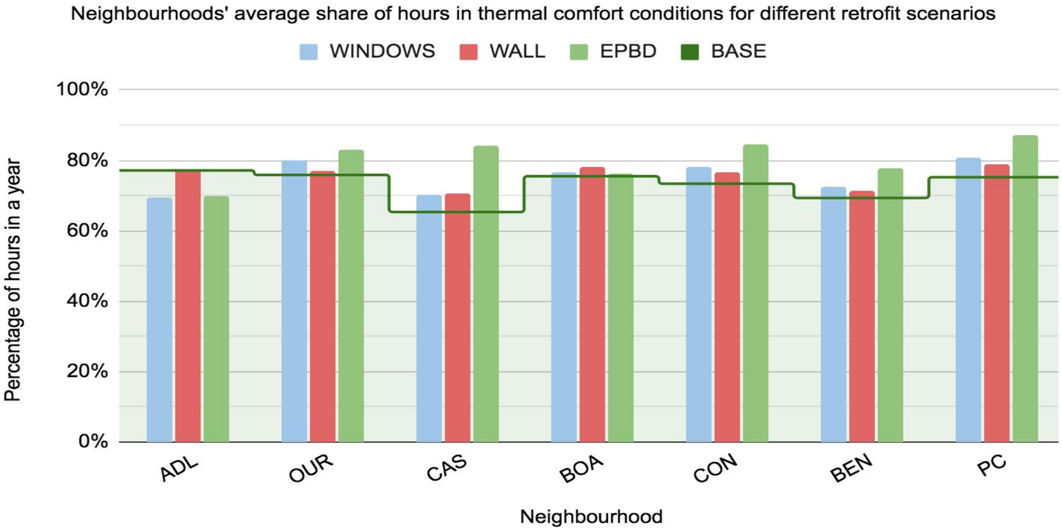


Figure 33: Average percentage of hours in a year spent in comfort conditions by residents of each neighbourhood, at the current situation (BASE - green line) and after the implementation of the retrofits WINDOWS (blue), WALL (red) and EPBD (green)

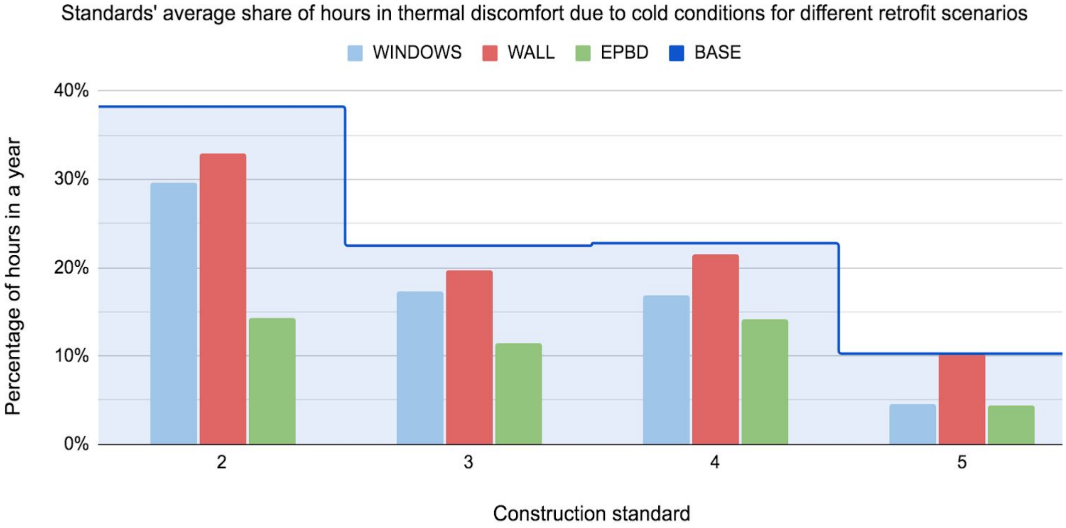


Figure 34: Average percentage of hours in a year spent in discomfort due to cold conditions in buildings of each standard, at the current situation (BASE - blue line) and after the implementation of the retrofits WINDOWS (blue), WALL (red) and EPBD (green)

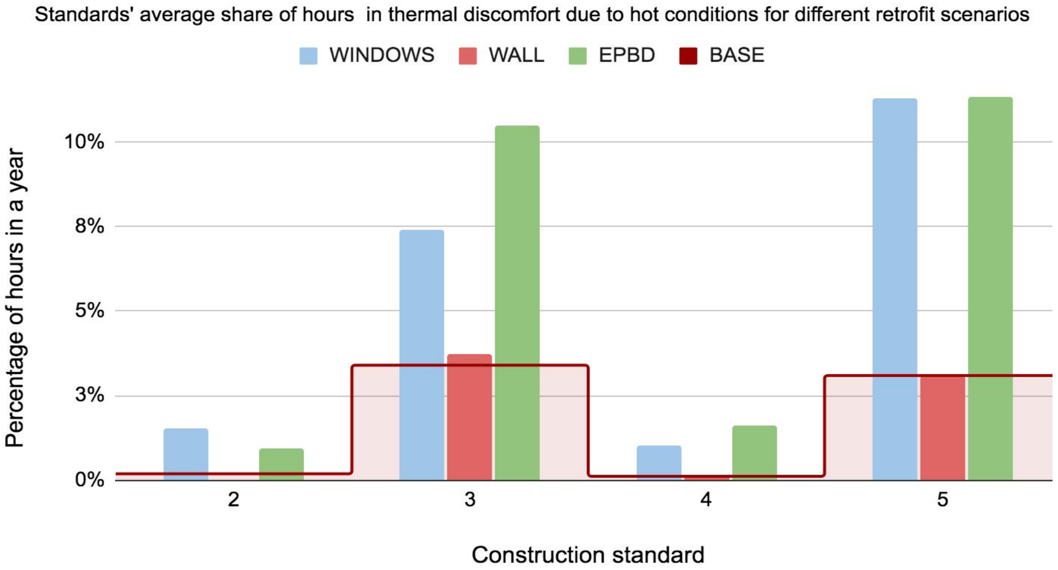


Figure 35: Average percentage of hours in a year spent in discomfort due to hot conditions in buildings of each standard, at the current situation (BASE - red line) and after the implementation of the retrofits WINDOWS (blue), WALL (red) and EPBD (green)

Figure 36 and Figure 37 summarize the differences between the current situation (Figure 36) and the EPBD scenario (Figure 37) by showing the share of time in which each building experiences thermal comfort (green) and thermal discomfort due to cold (blue) and hot conditions (red).

The improvement in terms of cold alleviation is evident: if a quarter of the buildings is currently experiencing cold for more than 4,000 hours per year (47% of the time - Figure 36), after the implementation of the retrofit no building exceeds the value of 3,800 hours (43% - Figure 37). Moreover, in Figure 37, it is possible to identify a clear demarcation between the buildings without heating, which stand cold for more than 2,000 hours per year (23% of the time), and the resting ones, which arrive at worst to 600 hours (7%).

A throwback comes in the form of overheating, in fact a tenth of the buildings would pass from living in hot conditions for around 1,600 hours per year (18% - Figure 36) to more than 3,000 hours (35% - Figure 37) after the retrofit.

Figure 38 shows the prevalence of comfort conditions in Condado in the current situation (Baseline) and its evolution after the implementation of the three retrofit measures proposed. Buildings in red represent low comfort conditions, for which internal temperatures remain in the comfort band (not too hot, nor too cold) for less than 70% of the time in the year.

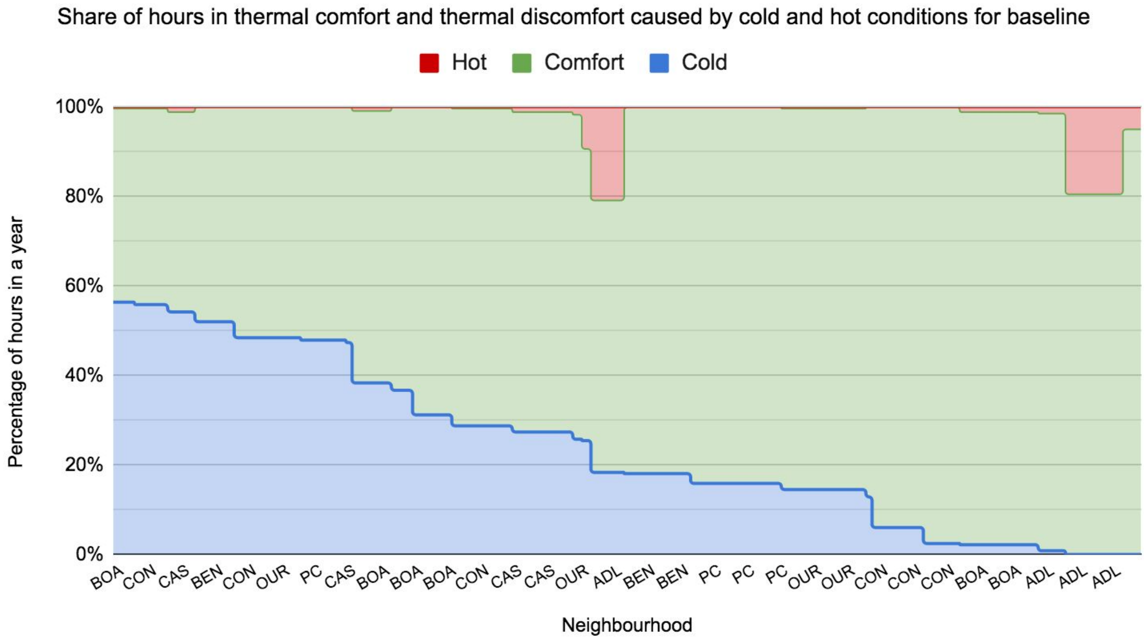


Figure 36: Share of time in which each building experiences thermal comfort (green) and thermal discomfort due to cold (blue) and hot conditions (red) at the current situation; sorted in descending order of time spent in cold conditions

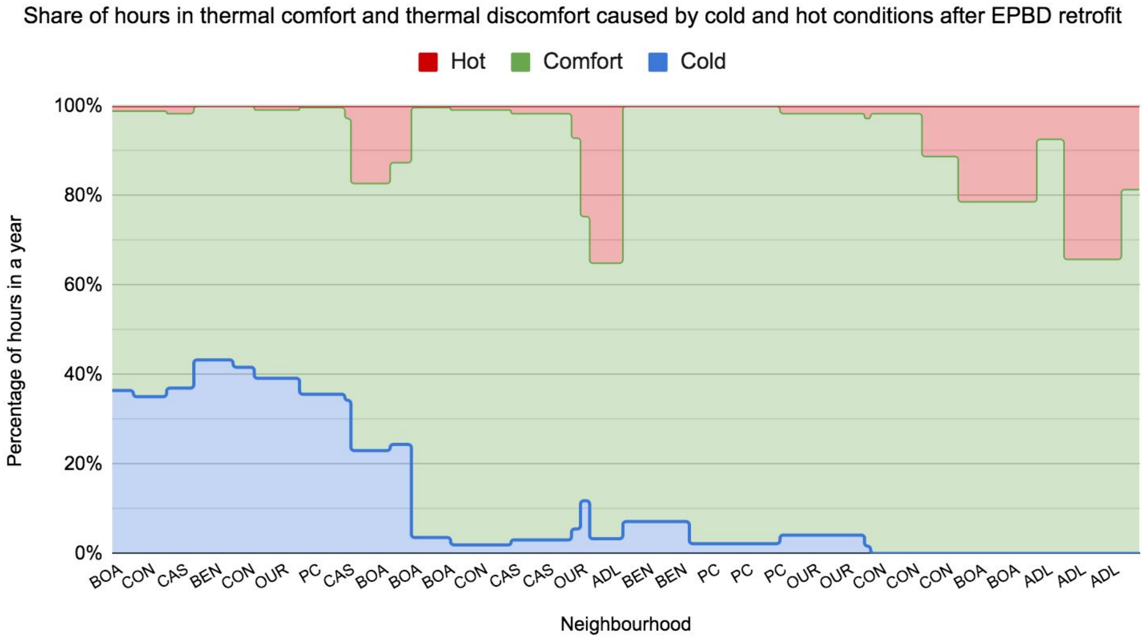


Figure 37: Share of time in which each building experiences thermal comfort (green) and thermal discomfort due to cold (blue) and hot conditions (red) after the implementation of EPBD retrofit

It can be seen that the most uncomfortable buildings are those without a heating system, marked by diagonal dashed lines. Once again, buildings of standard 2 (on the right band of each figure) are the most affected by the renovations, passing from less than 50% to almost 70% in case they do not have heating and even reaching the comfort threshold of 80% for the EPBD scenario in case they have.

In the last figure, it can be seen how some buildings (all of standard 3) decrease their comfort conditions with the EPBD retrofit because of overheating in summer, as already mentioned.

Additional information on the prevalence of thermal comfort in each neighbourhood is available in Annex E.

Percentage of time in comfort conditions

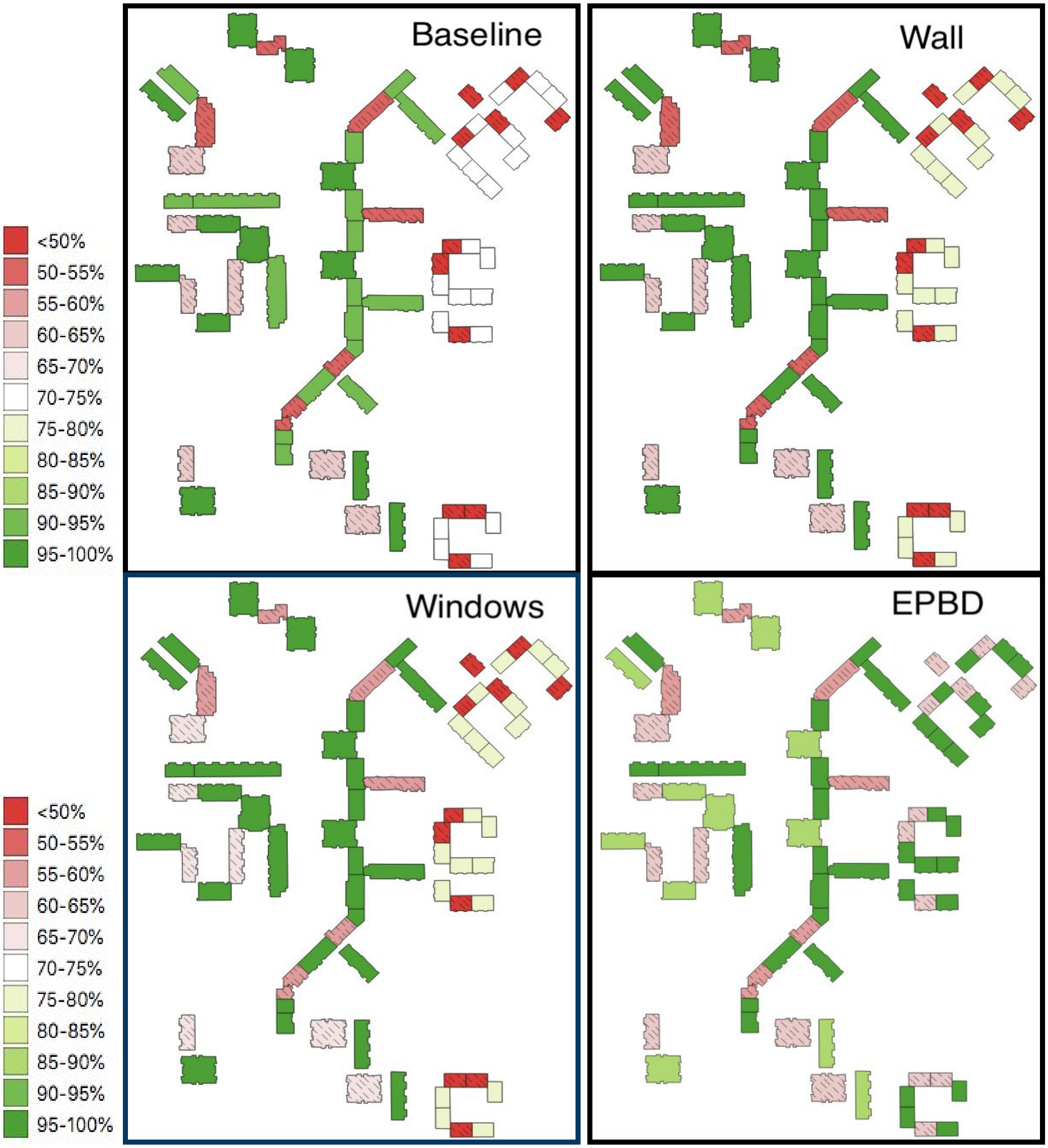


Figure 38: Prevalence of thermal comfort (green) and discomfort (red) conditions in Condado, at the current state (Baseline - top left) and after the implementation of the Wall (top right), Windows (bottom left) and EPBD (bottom right) retrofits; the buildings considered lacking a heating system are marked by diagonal dashed lines

Figure 39 focuses on discomfort caused by too cold temperatures, showing in blue the buildings experiencing cold for more than 20% of the time each year. Clearly, Figure 39 reiterates the considerations made for Figure 38, especially regarding the effect of a heating system on the fight against cold and the high margin of improvement coming with the renovation of older buildings.

Percentage of time in discomfort conditions caused by cold temperatures

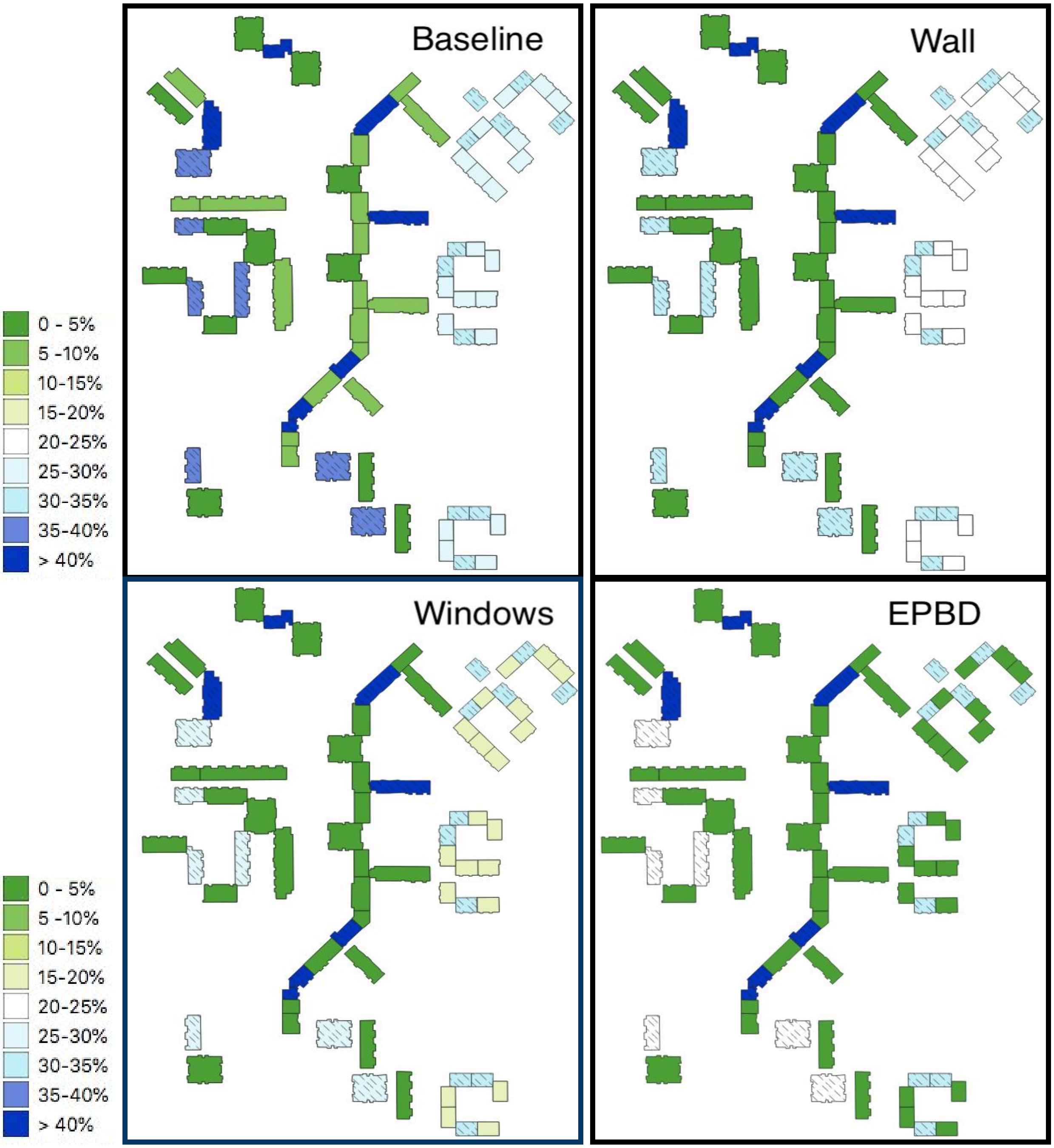


Figure 39: Prevalence of thermal discomfort due to cold conditions (red) in Condado, at the current state (Baseline - top left) and after the implementation of the Wall (top right), Windows (bottom left) and EPBD (bottom right) retrofits; the buildings considered lacking a heating system are marked by diagonal dashed lines

Figure 40 and figure 41 target the old buildings in Condado outlined before, comparing the evolution of the indoor temperature throughout the year in various circumstances.

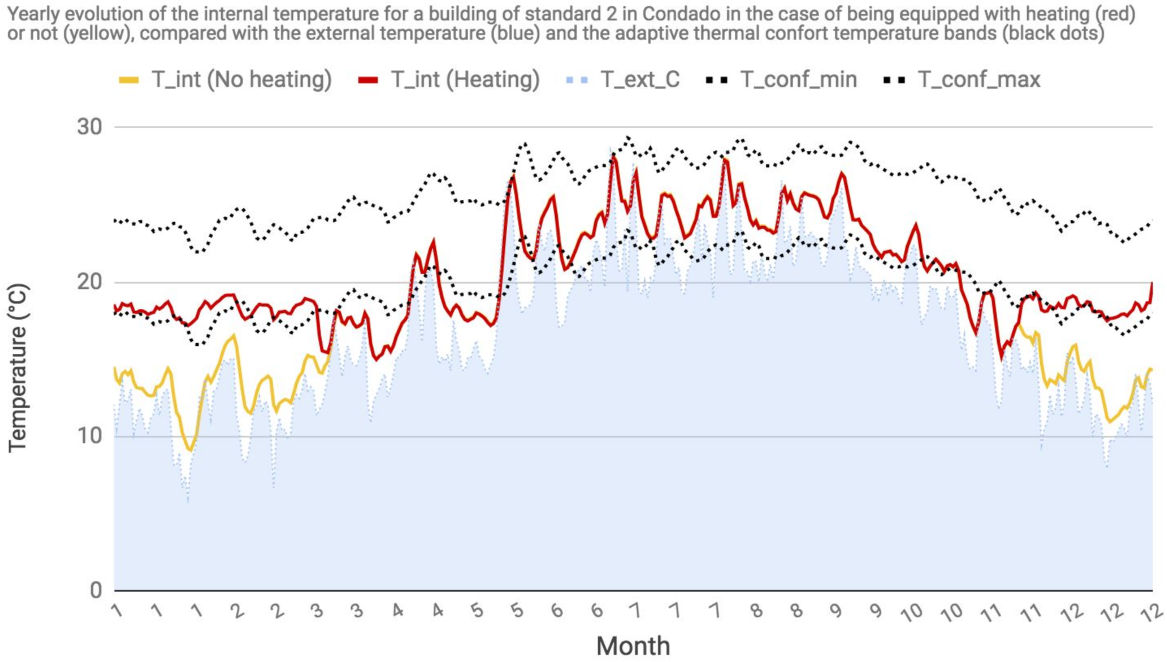


Figure 40: Yearly evolution of the internal temperature for a building of standard 2 in Condado in the case of being equipped with heating (red) or not (yellow), compared with the external temperature (blue) and the adaptive thermal comfort temperature bands (black dots)

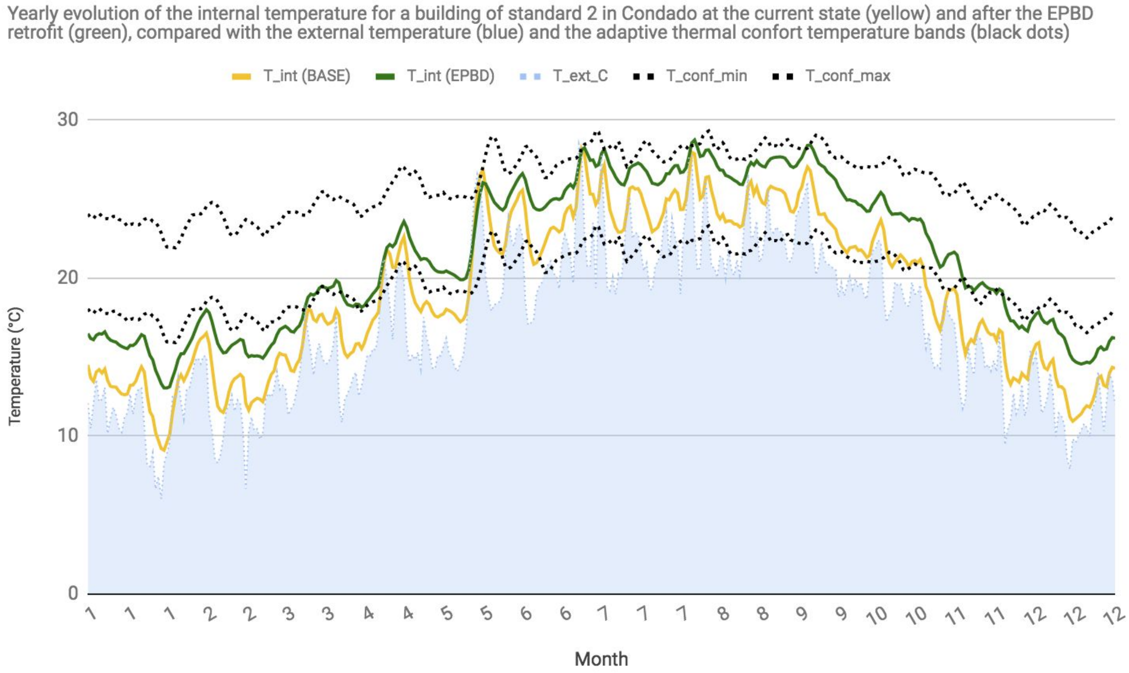


Figure 41: Yearly evolution of the internal temperature for a building of standard 2 in Condado without heating at the current state (yellow) and after the EPBD retrofit (green), compared with the external temperature (blue) and the adaptive thermal comfort temperature bands (black dots)

Figure 40 compares the yearly evolution of the internal temperature for a building of standard 2 in Condado without a heating system (yellow line) with an analogous building which, in turn, is equipped with electric heating (red line).

The two profiles only diverge in the chosen heating season, going from mid-November to mid-March. In these months the building with heating manages to keep a comfortable internal temperature for more than 80% of the time, despite it being very inefficient. On the other hand, the households without heating constantly live in uncomfortable conditions in these months, experiencing indoor temperatures as low as 9°C.

When considering the whole year, the building with heating remains in comfort conditions for 71% of the time, while the other for only 44%. All the discomfort caused to these old and inefficient buildings is due to too low temperatures, as evident when looking at Figure 40.

Figure 41 reveals what would happen to the building without a heating system just described if its envelope was to be renovated according to the EPBD scenario. For such a building, the decrease in the hours of cold is conspicuous and it comes without causing overheating in summer.

Nevertheless, the passive retrofit alone does not manage to reach comfort temperatures without having to use heating. Still, as shown in Figure 42, the absolute minimum temperature increases to 13°C and average indoor temperature in winter months passes from 12-13°C to around 16°C.

Also, around 1,700 hours of comfort are gained with the retrofit, leading to the conservation of comfort conditions for 64% of the time.

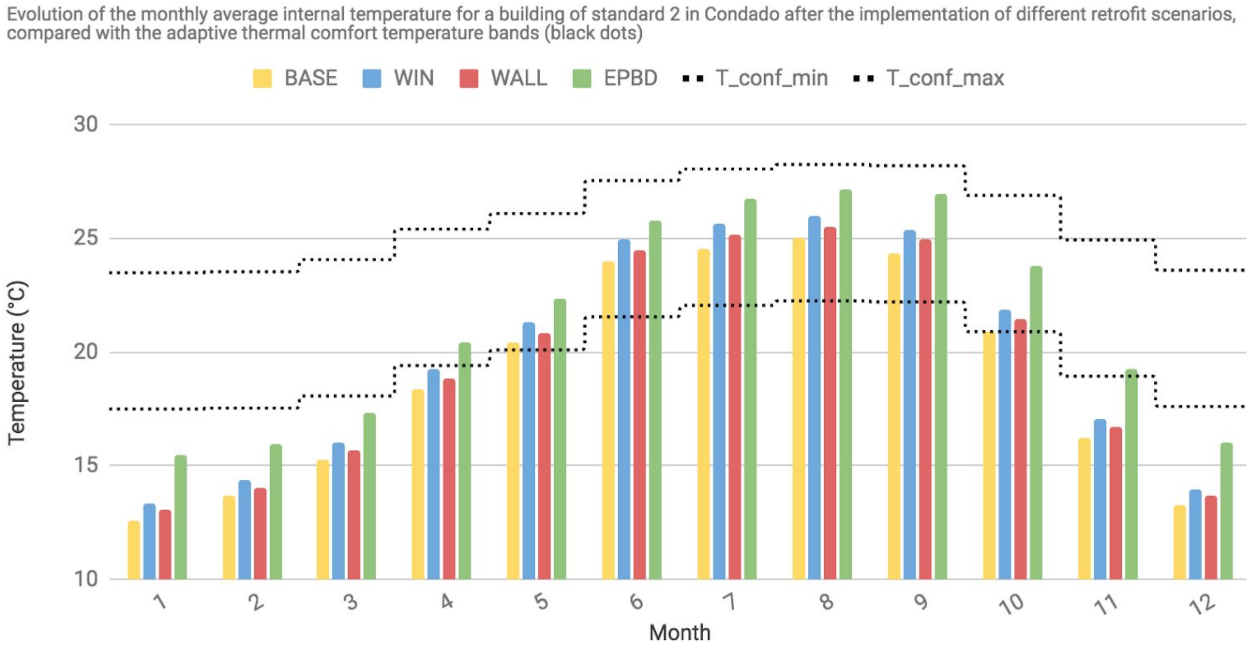


Figure 42: Evolution of the monthly average internal temperature for a building of standard 2 in Condado after the implementation of different retrofit scenarios, compared with the adaptive thermal comfort temperature bands (black dots)

Figure 43 presents the same analysis applied to an old building in Padre Cruz without heating, comparing the current indoor temperature with the one of the new building (equipped with heating) planned to relocate inhabitants of the degraded buildings. The intense cold experienced at the moment (58% of the time), with temperature basically equal outside and inside the home (reaching values as low as 8°C), disappears with the relocation. This benefit comes with the little cost of overheating, which increases in share from 3% to 13%.

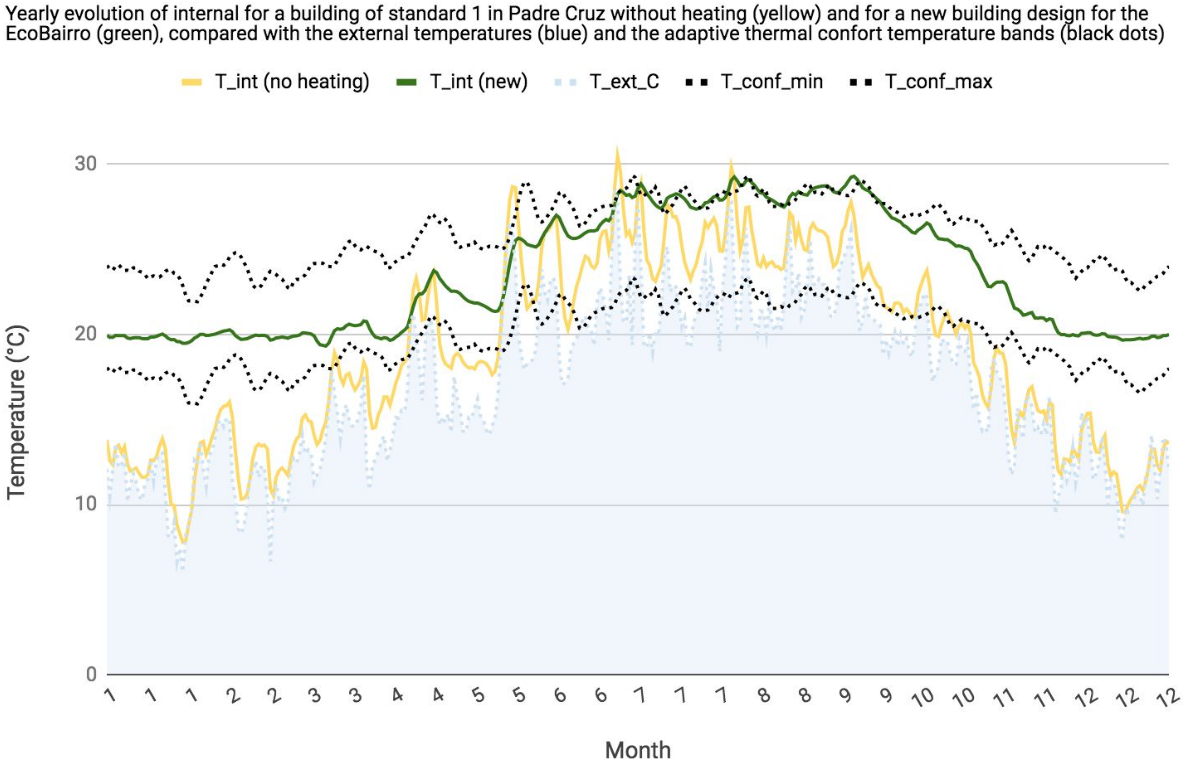


Figure 43: Yearly evolution of the internal temperature for a building of standard 1 in Padre Cruz without heating at the current state (yellow) and after the reconstruction planned by *Eco-Bairros* (green), compared with the external temperature (blue) and the adaptive thermal comfort temperature bands (black dots)

4.3 Economic analysis

4.3.1. Social tariffs vs. regular tariffs

On average, the annual monetary savings obtained with social tariffs range between 20€ to 30€ per household, depending on the type of retrofit. The idea to use those savings to cover for the retrofit investment becomes absurd when compared to average costs of around 2,000€ to 5,000€ per household.

When using regular tariffs the average savings slightly increase to 30-60€ per household. As shown in Table 9, this sum is still not enough to cover the renovation costs for the vast majority of buildings under all retrofit scenarios. These results confirm how classic economic examinations might be ineffectual when dealing with the renovation of public housing, likely because of the generally modest energy consumption of low-income households.

Table 9: Comparison of the average retrofit cost and annual bill savings per household, together with the share of buildings proving a feasible retrofit according to (i) positive Net Present Values (NPV - with a discount rate equal to 3%) or (ii) Return on Investments (ROI) lower than useful life years (Y - 25 for Windows & EPBD; 35 for Wall)

Retrofit scenario	**Average retrofit cost**	**Average bill savings**	**(i) buildings with NPV > 0€**	**(ii) buildings with ROI < Y**
WINDOWS	2,440€	38€/y	7%	8%
WALL	2,260€	30€/y	4%	9%
EPBD	5,430€	61€/y	1%	6%

For each household, the reconstruction works in Padre Cruz cost around 4,960€ and cause savings of around 150€ with the social tariff or 300€ with the regular tariff. These much higher margins make the project almost feasible even for the social tariff, with ROI equal to 32 years. Clearly, the use of regular tariffs results in a positive NPV and a viable ROI of 16 years.

4.3.2. NHS savings accounting

This chapter outlines the different results obtained applying to the economic analysis the two methodologies used to account for NHS savings (cost-effective vs. pragmatic).

Table 10 repeats the analysis made in chapter 3.3.1, by comparing the average renovation cost with the respective NHS savings derived by each retrofit scenario, calculated using both the cost-effective and the pragmatic methodology. With the first method, the NHS savings are from 4 to 10 times higher than the bill savings obtained with regular tariffs (661€/y vs. 61€/y for EPBD). On the other hand, with the pragmatic method, the NHS savings would exceed the bill savings only in the EPBD scenario (124€/y vs. 61€/y). This makes the EPBD retrofit much more reasonable than the others, with 43% of the buildings proving some economic benefits with the renovation (NPV>0€).

Table 10: Comparison of the average retrofit cost and annual NHS savings per household, calculated using both the cost-effective and the pragmatic methodology, together with the share of buildings proving a feasible retrofit according to a positive Net Present Values (NPV - with a discount rate equal to 3%), which is constant for both methodologies

Retrofit scenario	**Average retrofit cost**	**Cost-effective NHS savings**	**Pragmatic NHS savings**	**Buildings with NPV > 0€**
WINDOWS	2,440€	156€/y	29€/y	16%
WALL	2,260€	135€/y	25€/y	8%
EPBD	5,430€	661€/y	124€/y	43%

For the cost-effective method, the health savings generated by Padre Cruz reconstruction amount to around 2,000€/y per household, which added to the 150€ already saved with social tariff, give the investment an extremely beneficial ROI equal to 2.3 years.

When using the pragmatic method, the health savings reduce to around 380€/y, a value which still assures a very competitive ROI of 9.2 years.

In Figure 44 and Figure 46, it can be noted how the average building health expenses (yellow) increase with the age of the building. Using the HRQLC according to the cost-effective method, the yearly NHS expenses generally exceed the average renovation costs of Wall (red) and Windows (blue) retrofits. For older buildings, the yearly NHS expenses almost double the EPBD retrofit costs (106,000€/y vs. 62,000€) and the NHS savings derived by the EPBD retrofit (32,000€/y) even surpass the Windows and Wall retrofit costs (27,000€ & 26.000€).

Under these circumstances, four out of ten buildings present a ROI of less than 35 years for the EPBD scenario and more than half of them (23%) would repay the investment in less than 3 years. For the Windows and Wall scenarios, almost all the feasible interventions present ROIs lower than 2 years.

Figure 45 shows the correlation between current households' NHS expenditure (yellow), which is directly linked with the IVH levels of vulnerability, and the feasibility of the EPBD investment represented by the NPVs (green). It can be seen how for those households in the best (left - HRQLC = 0€) and the worst conditions (right - HRQLC = 19,620€) the investment is never covered by the NHS savings (NPV<0). These results hide the health benefits obtained by the most vulnerable households, whose thermal comfort do not reach the comfort threshold of 80% despite improving considerably.

This "all-or-nothing" condition is partly caused by the disproportionate magnitude of *HRQLC* as compared with the retrofit costs (Figure 44) and partly by the binary nature of the indicators (CI & EnI). In fact, if a retrofit measure manages to surpass a threshold of admissibility (CI>80% or EnI<1), then all the households living in that building are attributed significantly lower NHS expenses, if else no threshold is reached (e.g. CI=79% & EnI=1.05) the households would pay exactly the same.

For example, if a non-poor portuguese household living in inadmissible conditions (too high consumption and too little comfort) reached an electricity consumption of 1,210 $\frac{kWh}{p\cdot y}$ after a retrofit, then its EnI would become "Admissible" and its NHS expenses would drop by 2,900€/y. The same situation for a household in severe monetary poverty would cause NHS savings of 7,640€/y. However, the NHS savings would be null if the renovation of the same building only managed to reach a consumption of 1,230 $\frac{kWh}{p\cdot y}$.

Figure 46 and Figure 47 repeat the analysis made before applying the pragmatic methodology, which substitutes the *HRQLC* with the *NHS_cost*. While the NHS expenses and savings are around five times smaller, the patterns remain the same as for the cost-effective method. In particular, the amount of buildings presenting a positive ROI for EPBD retrofit (43%) remains constant for both methods. Indeed, the difference between Figure 45 and Figure 47 lay on the amplitude of the oscillation range of the NPV curve (which shrinks from 3,600,000€ to around 1,000,000€) and not on its shape.

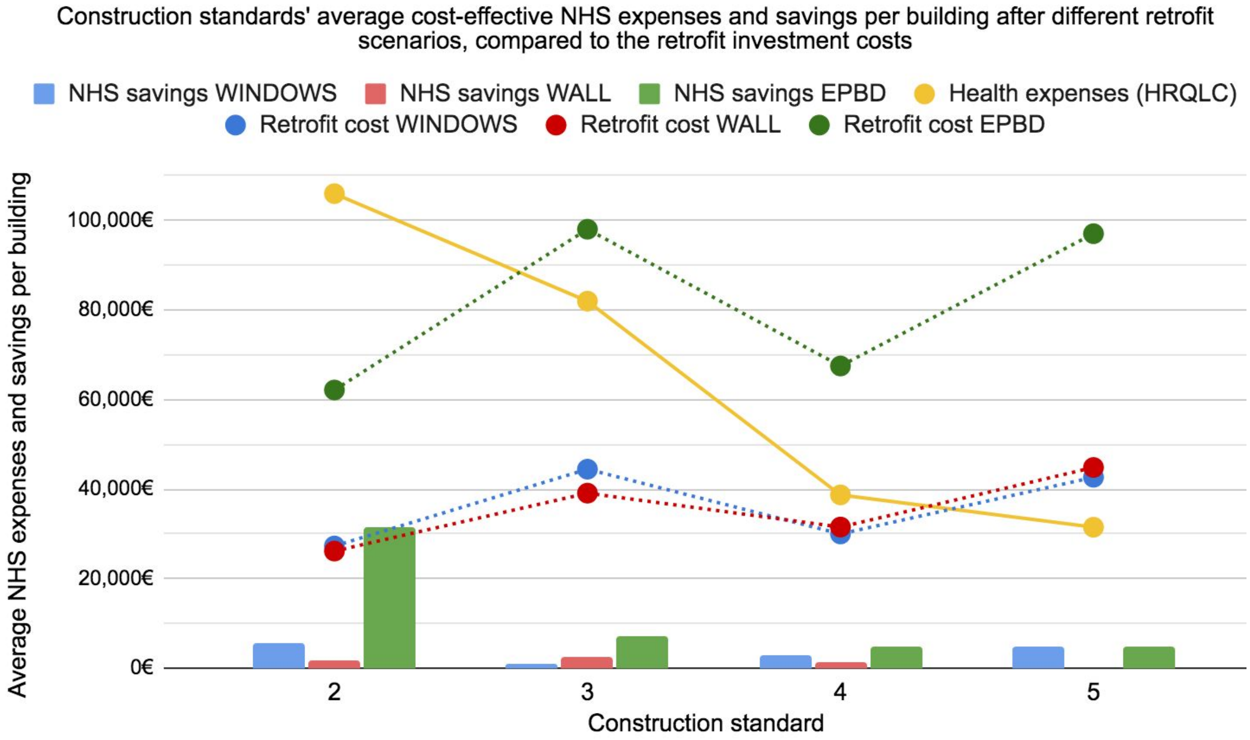


Figure 44: Construction standards' average building cost-effective NHS expenses (*HRQLC* - yellow line) and savings (columns) compared to the average renovation costs (dotted lines) derived from the Wall (red), Windows (blue) and EPBD (green) retrofits

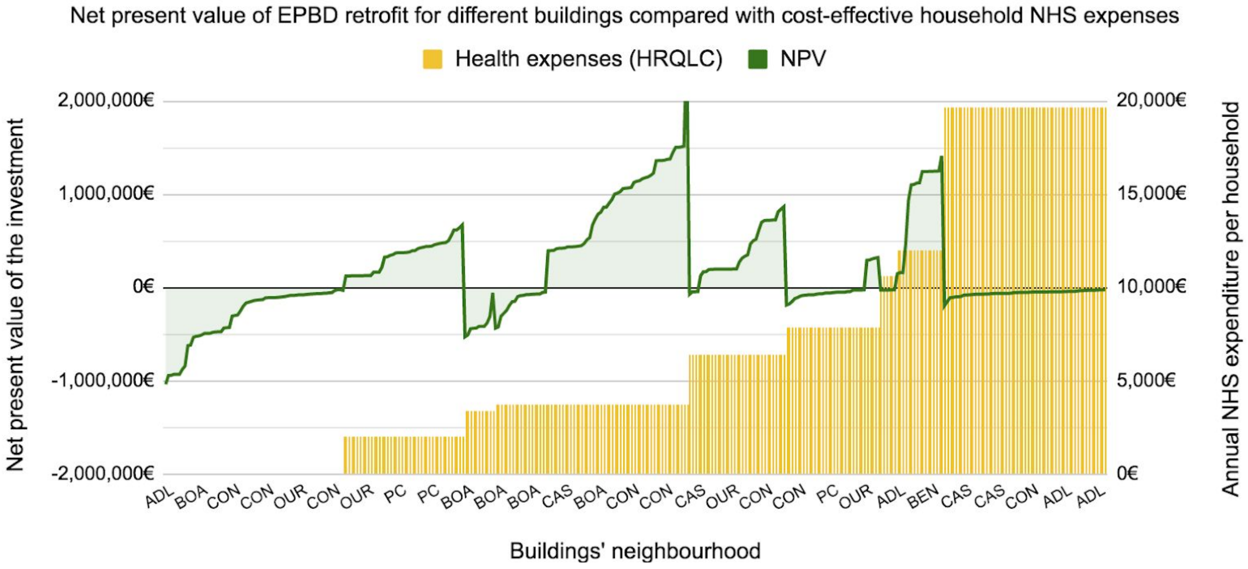


Figure 45: Trend ot the Net Present Value (NPV) of EPBD retrofits (green) compared to the households' cost-effective NHS expenses (*HRQLC* - yellow) in the current situation, organized in ascending order

The effects of the change in methodology can be appreciated when the results are aggregated at a neighbourhood level, as can be done comparing Figure 48 and Figure 49, which present the ROI of hypothetical renovations applied to all the buildings of each neighbourhood in the case study.

Using the cost-effective method (Figure 48), all the neighbourhoods present a very favourable ROI of less than 10 years for at least one of the scenarios. The EPBD renovation of the entire Alfredo Bensaúde could even be repaid in 1.8 years.

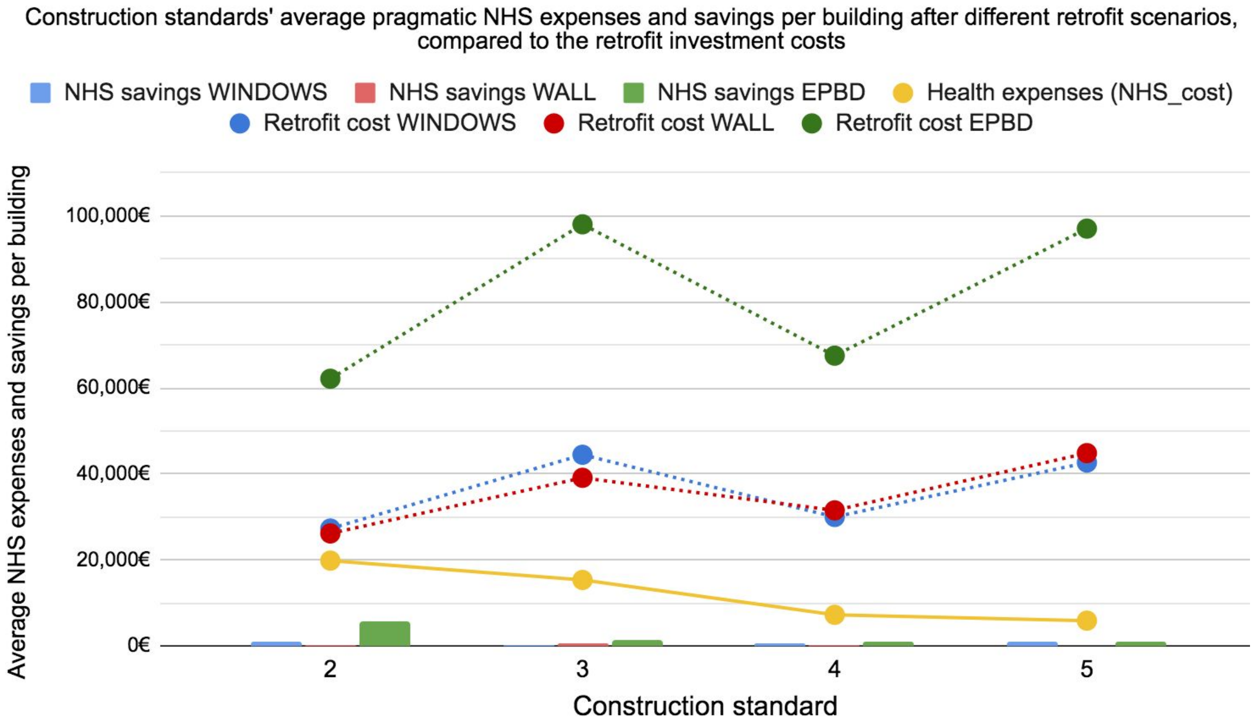


Figure 46: Construction standards' average building pragmatic NHS expenses (yellow line) and savings (columns) compared to the average renovation costs (dotted lines) derived from the Wall (red), Windows (blue) and EPBD (green) retrofits

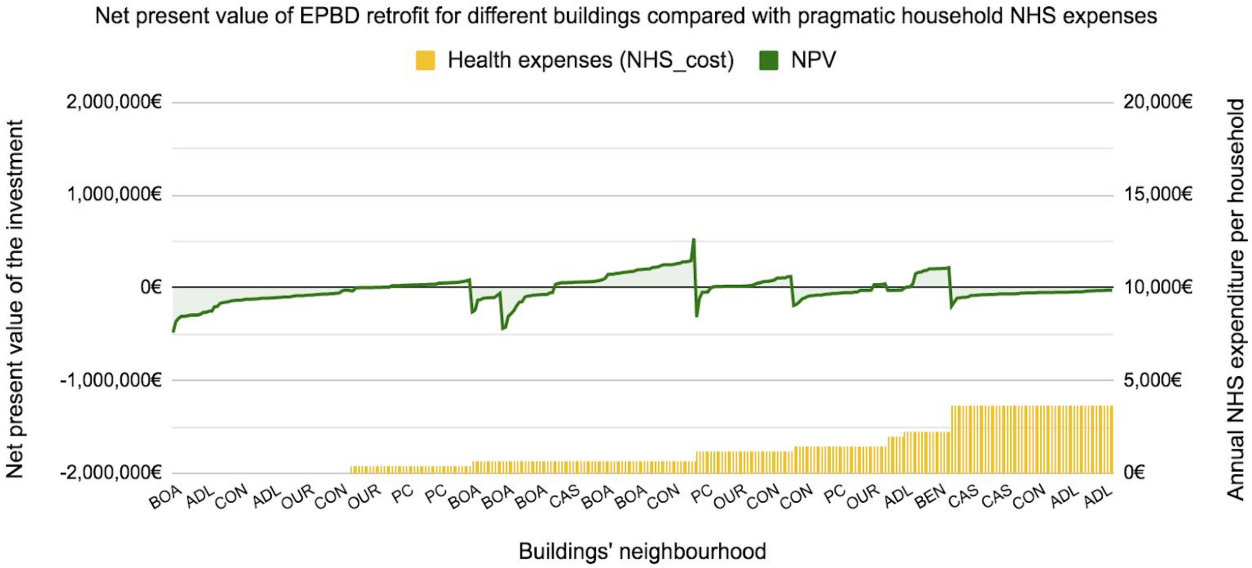


Figure 47: Trend ot the Net Present Value (NPV) of EPBD retrofits (green) compared to the households' pragmatic NHS expenses (yellow) in the current situation, organized in ascending order

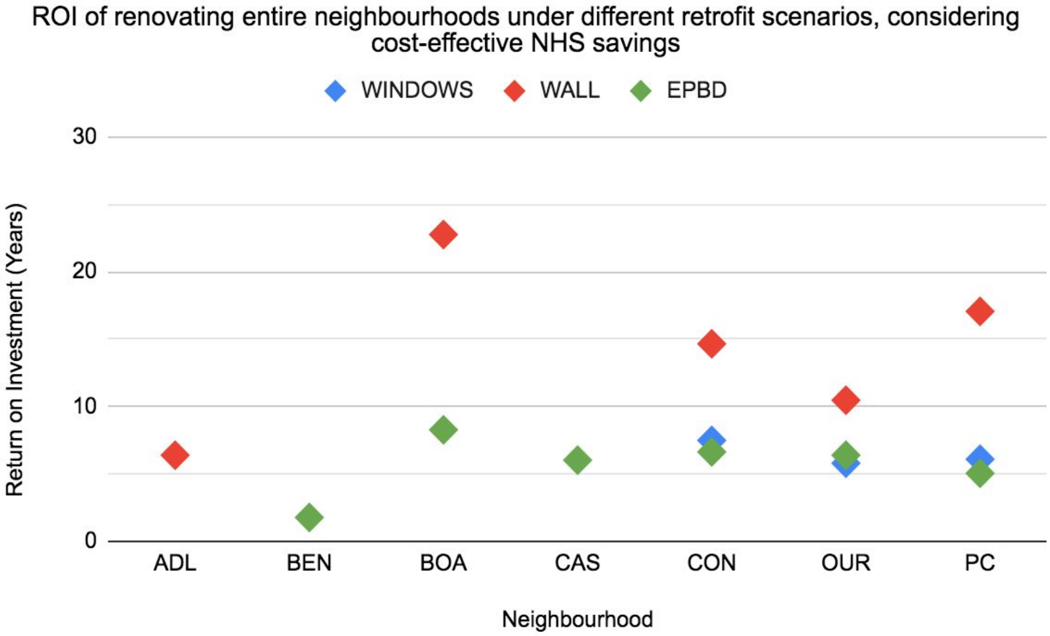


Figure 48: Return on Investment (ROI) of hypothetical Wall (red), Windows (blue) and EPBD (green) renovations applied to all the building of each neighbourhood in the case study, calculated using the cost-effective methodology

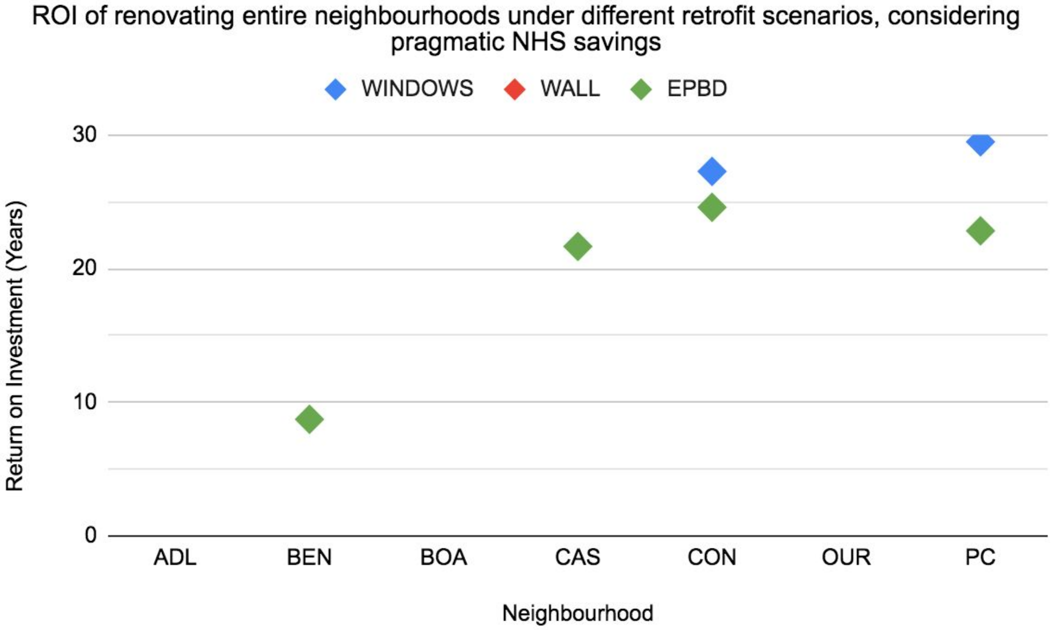


Figure 49: Return on Investment (ROI) of hypothetical Wall (red), Windows (blue) and EPBD (green) renovations applied to all the building of each neighbourhood in the case study, calculated using the pragmatic methodology

Using the pragmatic method, just four EPBD renovations would be feasible. Three neighbourhoods (Casalinho da Ajuda, Condado & Padre Cruz) show ROIs between 22 and 25 years, while this time the renovation of Alfredo Bensaúde could be repaid in 9 years (Figure 49).

The three other neighbourhoods (Alta de Lisboa, Boavista & Quinta do Ourives) disappear completely from the graph, despite showing very feasible investments in the precedent case. Of course, this does not mean that retrofitting some buildings in these neighbourhoods would not be feasible, indeed 22% of buildings in Boavista would still present positive NPVs as compared to 25% for the cost-effective method.

Using the pragmatic method, however, the NHS savings resulting from this fraction of buildings would not be as high as to unbalance the ROI of the renovation of the whole neighbourhood to the very low values shown in Figure 48.

4.4 Energy policy implications

By monetising the hidden benefits of housing retrofitting (e.g. health), this paper introduces a paradigm shift when it comes to invest in the renovation of public housing. Rather than a burden on the national budgets, the investments can be seen as a measure of social interest, which tackles at the same time the problems of climate change and social inequality and contributes to ensure welfare.

Tangibly speaking, using the results of this paper and following the example of the Portuguese long-term building renovation strategy (*ELPRE*), local authorities can draw a roadmap of investments aimed to reduce energy poverty in the city of Lisbon.

The wave of investment presents significant secondary benefits regarding the valorization of public assets and the encouragement of the promotion of public housing. Other public issues like social cohesion, safety, happiness and trust in the institutions could also be positively affected by this program.

Additionally, the energy simulation phase of the roadmap can help identify possible areas for the implementation of innovative practices in the energy sector, such as the establishment of local energy communities for the shared generation and consumption of renewable energy.

Finally, tenure types different from public housing can be approached by strengthening the cooperation between the departments of environment and health. In this way sectors intersectional policy efforts aiming to reduce fuel poverty can be designed, similarly to the Irish "Warmth and Wellbeing Scheme", in which free energy efficiency measures are delivered to people affected by a chronic respiratory disease.

5. Conclusions

Public health or fuel poverty are not always the primary concerns of energy efficiency retrofitting policies. This dimension is too often neglected when determining the economic feasibility of building retrofits, which may result in exclusion of vulnerable groups (less affluent and fuel poors) from subsidy schemes and further degradation of the already inefficient public housing stock.

By enhancing comfort conditions, passive retrofitting has shown a strong potential to tackle fuel poverty, mostly with positive effects on individuals' health and social life, while also contributing to the reduction of energy consumption and CO_2 emissions.

The *ELPRE* elaborated 38 building archetypes to characterize the national housing stock and analyse the potential of passive retrofitting. The *ELPRE* also estimated the economic benefits related to residents' health, calibrating them to 52€ saved per household each year.

This study develops a similar approach adjusted to the urban scale, using just 5 archetypes to identify the energy performance of Lisbon public housing stock. Focusing on a vulnerable fraction of the population, the economic implications of domestic thermal discomfort on public healthcare were examined with more detail. The NHS savings related to public housing retrofitting of the entire envelope resulted in 124€ saved per household each year on average, a value which is more than double than the national estimate given by *ELPRE*, which is sensible considering the precarious living conditions of the case study population.

The NHS savings derived from the renovation of the entire envelope would make the investment feasible for 43% of the buildings analysed. This kind of renovation is therefore recommended over individual replacement of envelope components, in particular windows and walls. As expected, when accounting for NHS savings, the retrofit action would be particularly viable for the neighbourhoods with the poorest population (Alfredo Bensaúde) or the oldest buildings (Condado, Casalinho da Ajuda).

The results obtained in Padre Cruz confirms that for processes of demolition and reconstruction, preferred when the buildings are too degraded or their configuration do not allow for intervention of the envelope, the large room for manoeuvre in the design phase leads to more favourable investments.

Several other methodologies have been developed to quantify the monetary benefits, in terms of NHS savings, of improving the thermal comfort conditions of households through passive retrofitting. All these studies rely on the collection of a considerable amount of data on the thermal properties of the buildings and the economic situation and the living conditions of their inhabitants, thus limiting the scale of the case study selected to a few households.

Not only is it the first time that a similar procedure is applied to the Portuguese context, but this study manages to examine a large sample of buildings while requiring relatively little inputs. The use of a bottom-up archetype approach enables the characterization and the energy performance simulation of around 1.800 buildings located in eight social neighbourhoods of Lisbon. The results of the analysis aggregated at a neighbourhood level provide useful insights into the feasibility of passive retrofit actions in terms of fuel poverty alleviation. Unlike the methodologies based on the cost-effectiveness value of a human life, made explicit by the HRQLC, this study proposes a more pragmatic way of accounting for NHS savings adjusted to the average per capita expenses on health in Portugal.

When discussing energy efficiency retrofitting policies, public authorities could and should take into account the long-term non-monetary benefits of housing renovations, especially regarding NHS relief. This study aims to bring to the discussion table the need for monetizing these hidden benefits derived by passive retrofitting and include them into the assessment of the investment. To do so, it provides a quick technique for establishing the current energy and thermal performance of entire (social) neighbourhoods and quantifying in monetary terms the advantages of their renovations, particularly on individuals' health.

This operation might open investment opportunities that currently do not exist for Portuguese vulnerable population. Indeed, the generally low energy consumption in Portugal contracts the margin of savings in the utility bills, a situation which intensifies for vulnerable groups (less affluent and energy poors).

The results of this study could allow local authorities to redesign public policies and the way public funding is allocated, tackling at the same time the problem of climate change and that of social inequality. This kind of strategy requires intersectional policy efforts in the environmental and health sectors, analogous to the Irish "Warmth and Wellbeing Scheme", in which free energy efficiency measures are delivered to people affected by a chronic respiratory disease.

The main limitation of this study lay on the high sensitivity of results on the thresholds' value chosen for the definition of the Comfort and Energy Indicators (CI & EnI). For example, by using the average domestic electricity consumption in Lisbon $(1,369\ \frac{kWh}{p \cdot y}))$ instead of the Portuguese value $(1,220\ \frac{kWh}{p \cdot y})$, the results would drastically change. Additionally, it is problematic to assess the validity of these thresholds or if changing them would lead the results closer to the actual situation described.

Furthermore, a sensitivity analysis on the simulation inputs has to be conducted to assess the validity of the assumptions. Finally, the results obtained by this study could be calibrated by measuring the energy consumption and thermal performance of real buildings belonging to the case study, but also by assessing the self-perceived health status and quality of life of their residents, both before and after the renovation.

6. References

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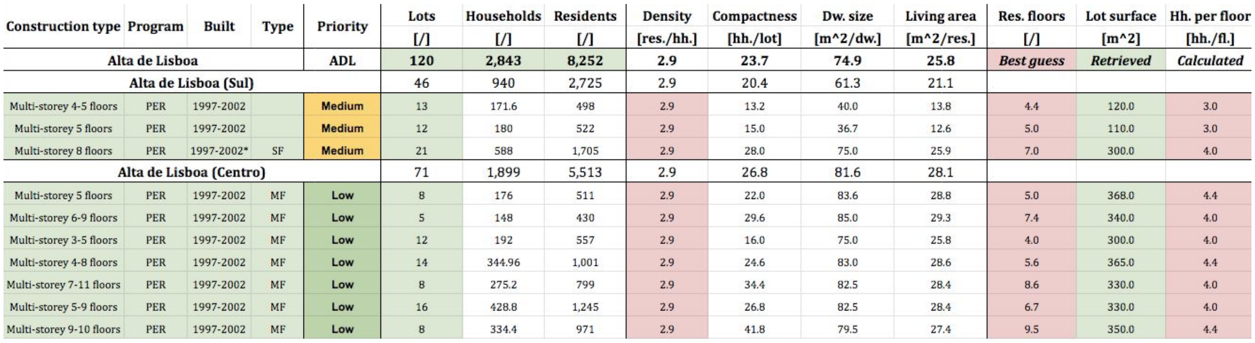
Annex A - Buildings in the case study area

The Annex presents extracts from a spreadsheet collecting the information on all the buildings in each neighbourhood of the study area, aggregated into affinity groups (or proto-archetypes). Table A1 to Table A6 show the construction characteristics (typology, public program, year of construction and class-size), the level of priority of intervention, the primary (number of lots, households and residents) and derived parameters (occupation density, building compactness, dwelling size and living area per person) used to characterize each group. Table A7 presents the same parameters, organizing the groups by construction standard.

A distinction between the values retrieved by some source (green), those estimated (red) and those calculated (white) is made explicit by changing the colour of the background.

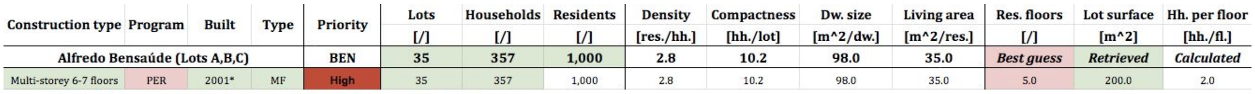
Table A1: Specifics of the public-owned residential buildings in Alta de Lisboa



Construction type	Program	Built	Type	Priority	Lots [/]	Households [/]	Residents [/]	Density [res./hh.]	Compactness [hh./lot]	Dw. size [m^2/dw.]	Living area [m^2/res.]	Res. floors [/]	Lot surface [m^2]	Hh. per floor [hh./fl.]
Alta de Lisboa				**ADL**	**120**	**2,843**	**8,252**	**2.9**	**23.7**	**74.9**	**25.8**	***Best guess***	***Retrieved***	***Calculated***
Alta de Lisboa (Sul)					46	940	2,725	2.9	20.4	61.3	21.1			
Multi-storey 4-5 floors	PER	1997-2002		Medium	13	171.6	498	2.9	13.2	40.0	13.8	4.4	120.0	3.0
Multi-storey 5 floors	PER	1997-2002		Medium	12	180	522	2.9	15.0	36.7	12.6	5.0	110.0	3.0
Multi-storey 8 floors	PER	1997-2002*	SF	Medium	21	588	1,705	2.9	28.0	75.0	25.9	7.0	300.0	4.0
Alta de Lisboa (Centro)					71	1,899	5,513	2.9	26.8	81.6	28.1			
Multi-storey 5 floors	PER	1997-2002	MF	Low	8	176	511	2.9	22.0	83.6	28.8	5.0	368.0	4.4
Multi-storey 6-9 floors	PER	1997-2002	MF	Low	5	148	430	2.9	29.6	85.0	29.3	7.4	340.0	4.0
Multi-storey 3-5 floors	PER	1997-2002	MF	Low	12	192	557	2.9	16.0	75.0	25.8	4.0	300.0	4.0
Multi-storey 4-8 floors	PER	1997-2002	MF	Low	14	344.96	1,001	2.9	24.6	83.0	28.6	5.6	365.0	4.4
Multi-storey 7-11 floors	PER	1997-2002	MF	Low	8	275.2	799	2.9	34.4	82.5	28.4	8.6	330.0	4.0
Multi-storey 5-9 floors	PER	1997-2002	MF	Low	16	428.8	1,245	2.9	26.8	82.5	28.4	6.7	330.0	4.0
Multi-storey 9-10 floors	PER	1997-2002	MF	Low	8	334.4	971	2.9	41.8	79.5	27.4	9.5	350.0	4.4

*partly renovated in 2015-2017: http://habitacao.cm-lisboa.pt/documentos/1308569883I1zQI1hn4Cl18JM3.pdf

Table A2: Specifics of the public-owned residential buildings in Afredo Bensaúde



Construction type	Program	Built	Type	Priority	Lots [/]	Households [/]	Residents [/]	Density [res./hh.]	Compactness [hh./lot]	Dw. size [m^2/dw.]	Living area [m^2/res.]	Res. floors [/]	Lot surface [m^2]	Hh. per floor [hh./fl.]
Alfredo Bensaúde (Lots A,B,C)				**BEN**	**35**	**357**	**1,000**	**2.8**	**10.2**	**98.0**	**35.0**	***Best guess***	***Retrieved***	***Calculated***
Multi-storey 6-7 floors	PER	2001*	MF	High	35	357	1,000	2.8	10.2	98.0	35.0	5.0	200.0	2.0

*partly renovated in 2015-2017: http://habitacao.cm-lisboa.pt/documentos/1308569883I1zQI1hn4Cl18JM3.pdf

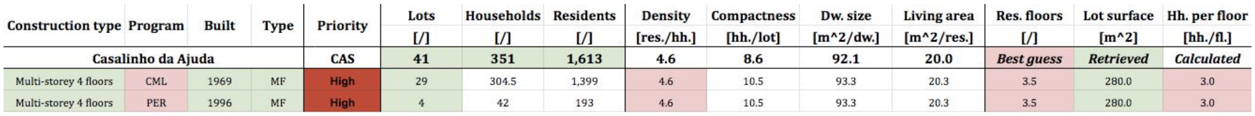
https://www.google.com/maps/place/GEBALIS/@38.779316,-9.117344,203a,35y,39.45t/data=!3m1!1e3!4m13!1m7!3m6!1s0xd193217e7432db1:0x4a5a0b22b1196201!2sAv.+Dr.+Alfredo+Bensa%C3%BAde,+Lisboa,+Portugal!3b1!8m2!3d38.7779703!4d-9.1140458!3m4!1s0xd1932168a37c669:0x834b812a4fc03e1f!8m2!3d38.7812581!4d-9.11825

Table A3: Specifics of the public-owned residential buildings in Bairro do Boavista

Construction type	Program	Built	Type	Priority	Lots [/]	Households [/]	Residents [/]	Density [res./hh.]	Compactness [hh./lot]	Dw. size [m^2/dw.]	Living area [m^2/res.]	Res. floors [/]	Lot surface [m^2]	Hh. per floor [hh./fl.]
Bairro de Boavista				**BOA**	**568**	**1,521**	**4,379**	**2.9**	**2.7**	**55.7**	**19.4**	***Best guess***	***Retrieved***	***Calculated***
Boavista (baracas)					510	510	1,224	2.9	1.0	24.0	10.0			
Detached 2 floors	CML	1975	SF	High	510	510	1,224	2.4	1.0	24.0	10.0	1.0	24.0	1.0
Boavista (predios)					58	1,011	3,155	3.1	17.4	71.7	23.0			
Detached 4 floors		1978	MF	Medium	4	80	248	3.1	20.0	60.0	19.4	4.0	300.0	5.0
Multi-storey 5 floors		1978	MF	Medium	4	80	248	3.1	20.0	51.3	16.5	5.0	205.0	4.0
Multi-storey 5 floors		1980-1984	MF	Medium	14	230	713	3.1	16.4	60.0	19.3	5.0	197.0	3.3
Multi-storey 5 floors	PIMP	1988-1996	MF	Medium	18	290	899	3.1	16.1	65.2	21.0	5.0	210.0	3.2
Multi-storey 7 floors	PIMP	1988-1996	MF	Medium	12	251	778	3.1	20.9	100.4	32.4	6.0	350.0	3.5

https://bairrodaboavista-lisboa.blogspot.com/p/historia-do-bairro_14.html

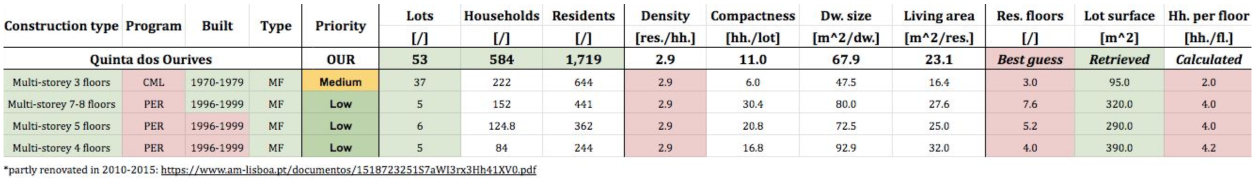
Table A4: Specifics of the public-owned residential buildings in Casalinho da Ajuda



Construction type	Program	Built	Type	Priority	Lots [/]	Households [/]	Residents [/]	Density [res./hh.]	Compactness [hh./lot]	Dw. size [m^2/dw.]	Living area [m^2/res.]	Res. floors [/]	Lot surface [m^2]	Hh. per floor [hh./fl.]
Casalinho da Ajuda				**CAS**	**41**	**351**	**1,613**	**4.6**	**8.6**	**92.1**	**20.0**	***Best guess***	***Retrieved***	***Calculated***
Multi-storey 4 floors	CML	1969	MF	High	29	304.5	1,399	4.6	10.5	93.3	20.3	3.5	280.0	3.0
Multi-storey 4 floors	PER	1996	MF	High	4	42	193	4.6	10.5	93.3	20.3	3.5	280.0	3.0

https://pt.wikipedia.org/wiki/Casalinho_da_Ajuda

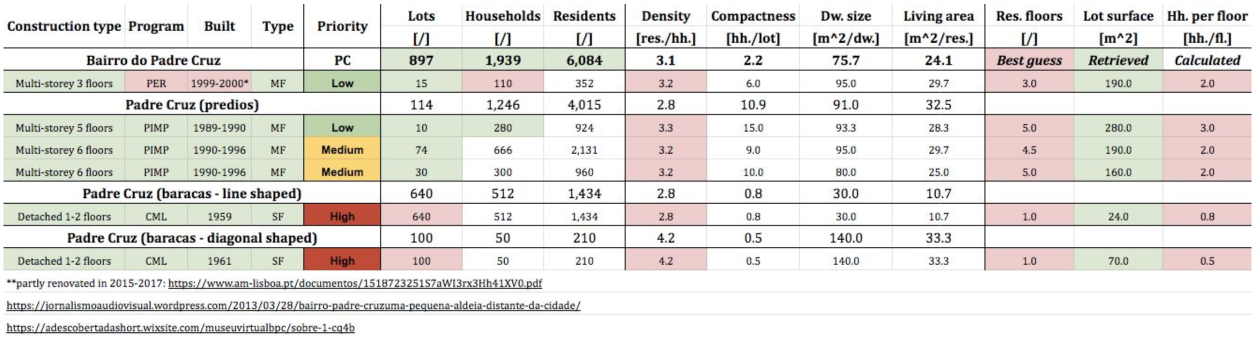
Table A5: Specifics of the public-owned residential buildings in Quinta dos Ourives



Construction type	Program	Built	Type	Priority	Lots	Households	Residents	Density	Compactness	Dw. size	Living area	Res. floors	Lot surface	Hh. per floor
					[/]	[/]	[/]	[res./hh.]	[hh./lot]	[m^2/dw.]	[m^2/res.]	[/]	[m^2]	[hh./fl.]
Quinta dos Ourives				**OUR**	**53**	**584**	**1,719**	**2.9**	**11.0**	**67.9**	**23.1**	***Best guess***	***Retrieved***	***Calculated***
Multi-storey 3 floors	CML	1970-1979	MF	Medium	37	222	644	2.9	6.0	47.5	16.4	3.0	95.0	2.0
Multi-storey 7-8 floors	PER	1996-1999	MF	Low	5	152	441	2.9	30.4	80.0	27.6	7.6	320.0	4.0
Multi-storey 5 floors	PER	1996-1999	MF	Low	6	124.8	362	2.9	20.8	72.5	25.0	5.2	290.0	4.0
Multi-storey 4 floors	PER	1996-1999	MF	Low	5	84	244	2.9	16.8	92.9	32.0	4.0	390.0	4.2

*partly renovated in 2010-2015: https://www.am-lisboa.pt/documentos/1518723251S7aWI3rx3Hh41XV0.pdf

Table A6: Specifics of the public-owned residential buildings in Bairro do Padre Cruz



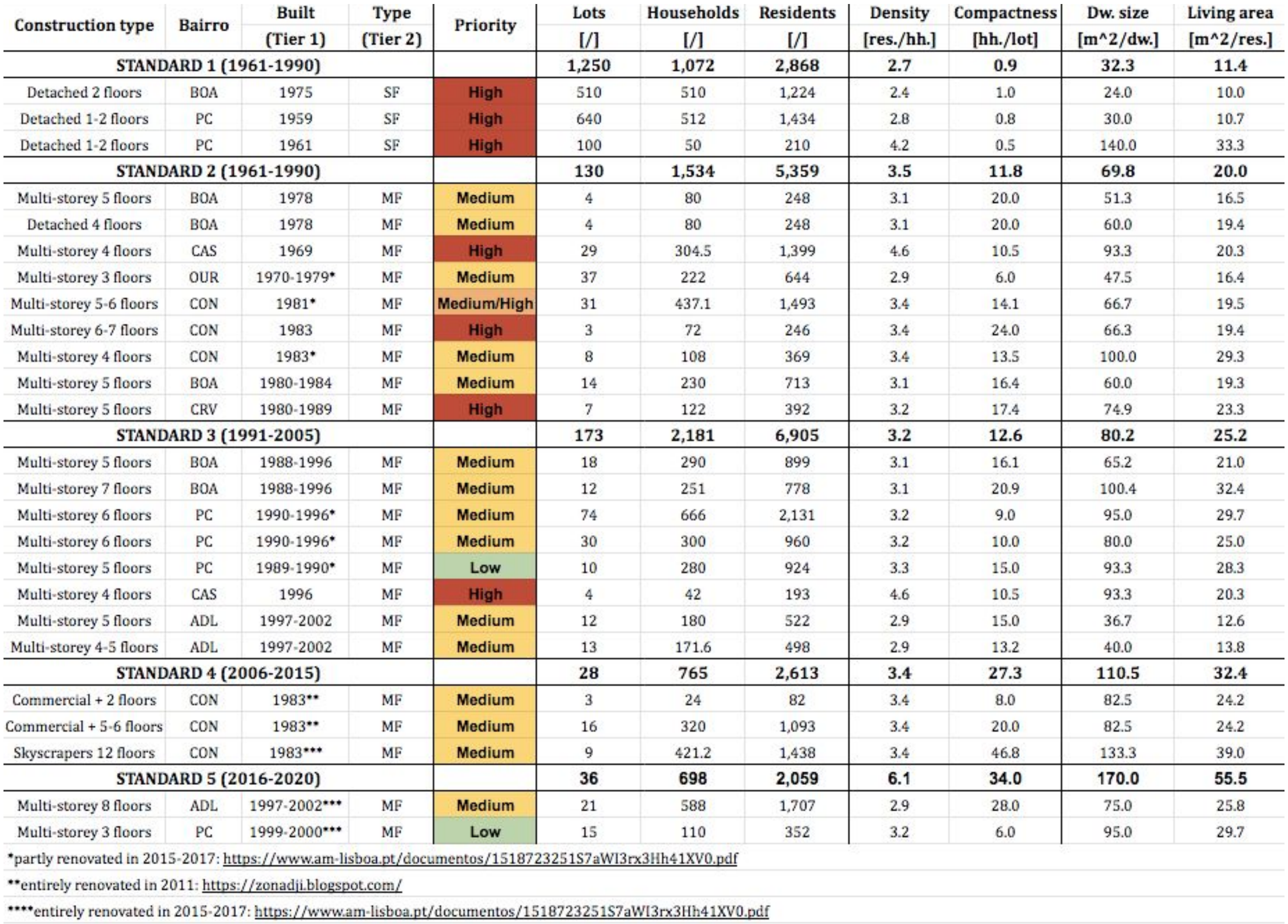
Construction type	Program	Built	Type	Priority	Lots	Households	Residents	Density	Compactness	Dw. size	Living area	Res. floors	Lot surface	Hh. per floor
					[/]	[/]	[/]	[res./hh.]	[hh./lot]	[m^2/dw.]	[m^2/res.]	[/]	[m^2]	[hh./fl.]
Bairro do Padre Cruz				**PC**	**897**	**1,939**	**6,084**	**3.1**	**2.2**	**75.7**	**24.1**	***Best guess***	***Retrieved***	***Calculated***
Multi-storey 3 floors	PER	1999-2000*	MF	Low	15	110	352	3.2	6.0	95.0	29.7	3.0	190.0	2.0
Padre Cruz (predios)					114	1,246	4,015	2.8	10.9	91.0	32.5			
Multi-storey 5 floors	PIMP	1989-1990	MF	Low	10	280	924	3.3	15.0	93.3	28.3	5.0	280.0	3.0
Multi-storey 6 floors	PIMP	1990-1996	MF	Medium	74	666	2,131	3.2	9.0	95.0	29.7	4.5	190.0	2.0
Multi-storey 6 floors	PIMP	1990-1996	MF	Medium	30	300	960	3.2	10.0	80.0	25.0	5.0	160.0	2.0
Padre Cruz (baracas - line shaped)					640	512	1,434	2.8	0.8	30.0	10.7			
Detached 1-2 floors	CML	1959	SF	High	640	512	1,434	2.8	0.8	30.0	10.7	1.0	24.0	0.8
Padre Cruz (baracas - diagonal shaped)					100	50	210	4.2	0.5	140.0	33.3			
Detached 1-2 floors	CML	1961	SF	High	100	50	210	4.2	0.5	140.0	33.3	1.0	70.0	0.5

**partly renovated in 2015-2017: https://www.am-lisboa.pt/documentos/1518723251S7aWI3rx3Hh41XV0.pdf

https://jornalismoaudiovisual.wordpress.com/2013/03/28/bairro-padre-cruzuma-pequena-aldeia-distante-da-cidade/

https://adescobertadashort.wixsite.com/museuvirtualbpc/sobre-1-cq4b

Table A7: Specifics of the buildings in the seven neighbourhoods of the case study, organized by construction standard



Construction type	Bairro	Built	Type	Priority	Lots	Households	Residents	Density	Compactness	Dw. size	Living area
		(Tier 1)	(Tier 2)		[/]	[/]	[/]	[res./hh.]	[hh./lot]	[m^2/dw.]	[m^2/res.]
STANDARD 1 (1961-1990)					**1,250**	**1,072**	**2,868**	**2.7**	**0.9**	**32.3**	**11.4**
Detached 2 floors	BOA	1975	SF	High	510	510	1,224	2.4	1.0	24.0	10.0
Detached 1-2 floors	PC	1959	SF	High	640	512	1,434	2.8	0.8	30.0	10.7
Detached 1-2 floors	PC	1961	SF	High	100	50	210	4.2	0.5	140.0	33.3
STANDARD 2 (1961-1990)					**130**	**1,534**	**5,359**	**3.5**	**11.8**	**69.8**	**20.0**
Multi-storey 5 floors	BOA	1978	MF	Medium	4	80	248	3.1	20.0	51.3	16.5
Detached 4 floors	BOA	1978	MF	Medium	4	80	248	3.1	20.0	60.0	19.4
Multi-storey 4 floors	CAS	1969	MF	High	29	304.5	1,399	4.6	10.5	93.3	20.3
Multi-storey 3 floors	OUR	1970-1979*	MF	Medium	37	222	644	2.9	6.0	47.5	16.4
Multi-storey 5-6 floors	CON	1981*	MF	Medium/High	31	437.1	1,493	3.4	14.1	66.7	19.5
Multi-storey 6-7 floors	CON	1983	MF	High	3	72	246	3.4	24.0	66.3	19.4
Multi-storey 4 floors	CON	1983*	MF	Medium	8	108	369	3.4	13.5	100.0	29.3
Multi-storey 5 floors	BOA	1980-1984	MF	Medium	14	230	713	3.1	16.4	60.0	19.3
Multi-storey 5 floors	CRV	1980-1989	MF	High	7	122	392	3.2	17.4	74.9	23.3
STANDARD 3 (1991-2005)					**173**	**2,181**	**6,905**	**3.2**	**12.6**	**80.2**	**25.2**
Multi-storey 5 floors	BOA	1988-1996	MF	Medium	18	290	899	3.1	16.1	65.2	21.0
Multi-storey 7 floors	BOA	1988-1996	MF	Medium	12	251	778	3.1	20.9	100.4	32.4
Multi-storey 6 floors	PC	1990-1996*	MF	Medium	74	666	2,131	3.2	9.0	95.0	29.7
Multi-storey 6 floors	PC	1990-1996*	MF	Medium	30	300	960	3.2	10.0	80.0	25.0
Multi-storey 5 floors	PC	1989-1990*	MF	Low	10	280	924	3.3	15.0	93.3	28.3
Multi-storey 4 floors	CAS	1996	MF	High	4	42	193	4.6	10.5	93.3	20.3
Multi-storey 5 floors	ADL	1997-2002	MF	Medium	12	180	522	2.9	15.0	36.7	12.6
Multi-storey 4-5 floors	ADL	1997-2002	MF	Medium	13	171.6	498	2.9	13.2	40.0	13.8
STANDARD 4 (2006-2015)					**28**	**765**	**2,613**	**3.4**	**27.3**	**110.5**	**32.4**
Commercial + 2 floors	CON	1983**	MF	Medium	3	24	82	3.4	8.0	82.5	24.2
Commercial + 5-6 floors	CON	1983**	MF	Medium	16	320	1,093	3.4	20.0	82.5	24.2
Skyscrapers 12 floors	CON	1983***	MF	Medium	9	421.2	1,438	3.4	46.8	133.3	39.0
STANDARD 5 (2016-2020)					**36**	**698**	**2,059**	**6.1**	**34.0**	**170.0**	**55.5**
Multi-storey 8 floors	ADL	1997-2002***	MF	Medium	21	588	1,707	2.9	28.0	75.0	25.8
Multi-storey 3 floors	PC	1999-2000***	MF	Low	15	110	352	3.2	6.0	95.0	29.7

*partly renovated in 2015-2017: https://www.am-lisboa.pt/documentos/1518723251S7aWI3rx3Hh41XV0.pdf

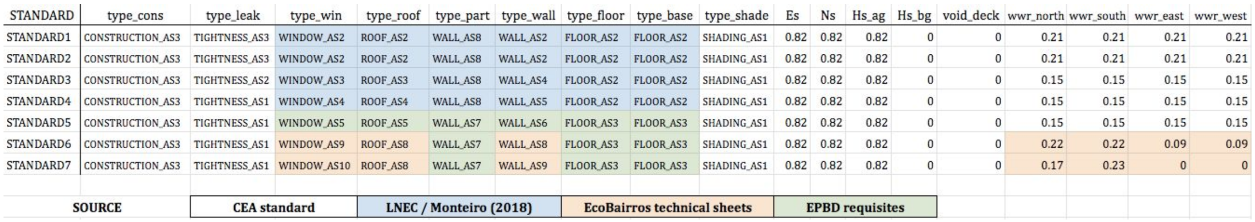
**entirely renovated in 2011: https://zonadji.blogspot.com/

****entirely renovated in 2015-2017: https://www.am-lisboa.pt/documentos/1518723251S7aWI3rx3Hh41XV0.pdf

Annex B - Definition of Lisbon construction standards

The Annex presents extracts from a spreadsheet collecting all the information, structured as required by CEA, needed to define the seven construction standards of Lisbon public housing stock (which are described in sections 3.2 and 3.3). The Annex contains information on the elemental components of the envelope, the HVAC and the supply systems as well as their configuration in the definition of the construction standards.

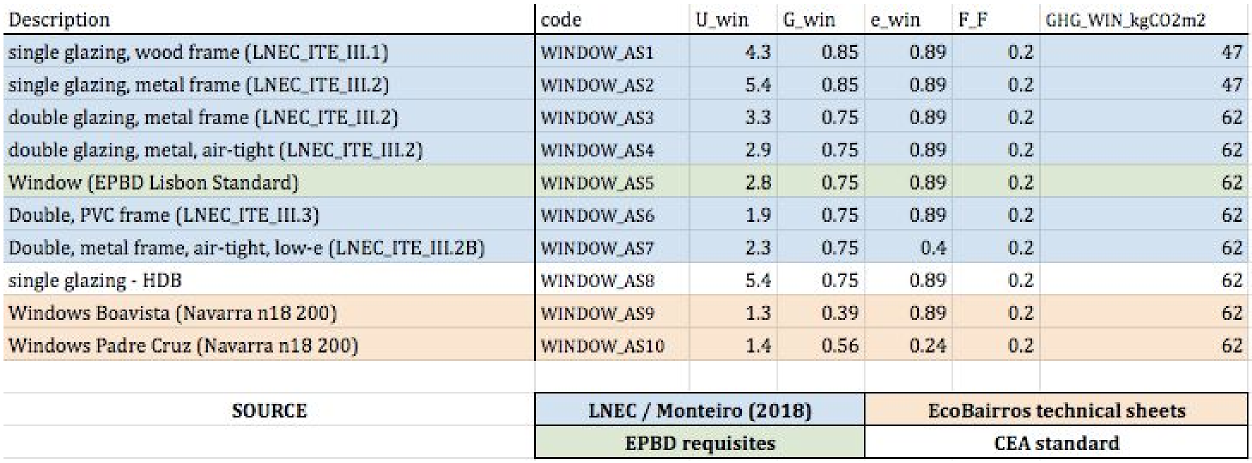
Table B1: Definition of the seven construction standards for Lisbon according to CEA requisites



STANDARD	type_cons	type_leak	type_win	type_roof	type_part	type_wall	type_floor	type_base	type_shade	Es	Ns	Hs_ag	Hs_bg	void_deck	wwr_north	wwr_south	wwr_east	wwr_west
STANDARD1	CONSTRUCTION_AS3	TIGHTNESS_AS3	WINDOW_AS2	ROOF_AS2	WALL_AS8	WALL_AS2	FLOOR_AS2	FLOOR_AS2	SHADING_AS1	0.82	0.82	0.82	0	0	0.21	0.21	0.21	0.21
STANDARD2	CONSTRUCTION_AS3	TIGHTNESS_AS3	WINDOW_AS2	ROOF_AS2	WALL_AS8	WALL_AS2	FLOOR_AS2	FLOOR_AS2	SHADING_AS1	0.82	0.82	0.82	0	0	0.21	0.21	0.21	0.21
STANDARD3	CONSTRUCTION_AS3	TIGHTNESS_AS2	WINDOW_AS3	ROOF_AS3	WALL_AS8	WALL_AS4	FLOOR_AS2	FLOOR_AS2	SHADING_AS1	0.82	0.82	0.82	0	0	0.15	0.15	0.15	0.15
STANDARD4	CONSTRUCTION_AS3	TIGHTNESS_AS1	WINDOW_AS4	ROOF_AS4	WALL_AS8	WALL_AS5	FLOOR_AS2	FLOOR_AS2	SHADING_AS1	0.82	0.82	0.82	0	0	0.15	0.15	0.15	0.15
STANDARD5	CONSTRUCTION_AS3	TIGHTNESS_AS1	WINDOW_AS5	ROOF_AS5	WALL_AS7	WALL_AS6	FLOOR_AS3	FLOOR_AS3	SHADING_AS1	0.82	0.82	0.82	0	0	0.15	0.15	0.15	0.15
STANDARD6	CONSTRUCTION_AS3	TIGHTNESS_AS1	WINDOW_AS9	ROOF_AS8	WALL_AS7	WALL_AS8	FLOOR_AS3	FLOOR_AS3	SHADING_AS1	0.82	0.82	0.82	0	0	0.22	0.22	0.09	0.09
STANDARD7	CONSTRUCTION_AS3	TIGHTNESS_AS1	WINDOW_AS10	ROOF_AS8	WALL_AS7	WALL_AS9	FLOOR_AS3	FLOOR_AS3	SHADING_AS1	0.82	0.82	0.82	0	0	0.17	0.23	0	0

SOURCE	CEA standard	LNEC / Monteiro (2018)	EcoBairros technical sheets	EPBD requisites

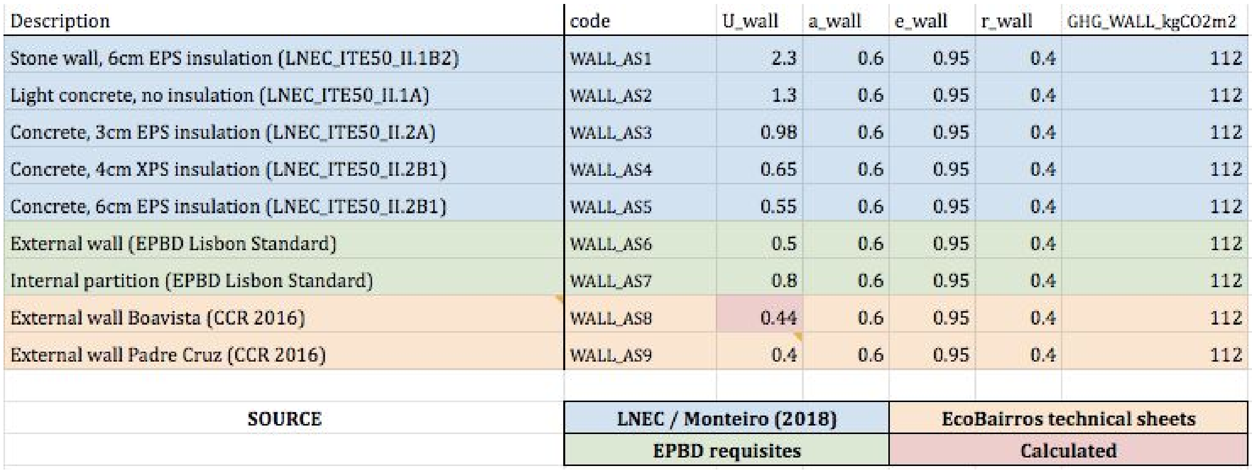
Table B2: Definition of elemental windows for Lisbon according to CEA requisites



Description	code	U_win	G_win	e_win	F_F	GHG_WIN_kgCO2m2
single glazing, wood frame (LNEC_ITE_III.1)	WINDOW_AS1	4.3	0.85	0.89	0.2	47
single glazing, metal frame (LNEC_ITE_III.2)	WINDOW_AS2	5.4	0.85	0.89	0.2	47
double glazing, metal frame (LNEC_ITE_III.2)	WINDOW_AS3	3.3	0.75	0.89	0.2	62
double glazing, metal, air-tight (LNEC_ITE_III.2)	WINDOW_AS4	2.9	0.75	0.89	0.2	62
Window (EPBD Lisbon Standard)	WINDOW_AS5	2.8	0.75	0.89	0.2	62
Double, PVC frame (LNEC_ITE_III.3)	WINDOW_AS6	1.9	0.75	0.89	0.2	62
Double, metal frame, air-tight, low-e (LNEC_ITE_III.2B)	WINDOW_AS7	2.3	0.75	0.4	0.2	62
single glazing - HDB	WINDOW_AS8	5.4	0.75	0.89	0.2	62
Windows Boavista (Navarra n18 200)	WINDOW_AS9	1.3	0.39	0.89	0.2	62
Windows Padre Cruz (Navarra n18 200)	WINDOW_AS10	1.4	0.56	0.24	0.2	62

SOURCE	LNEC / Monteiro (2018)	EcoBairros technical sheets
	EPBD requisites	CEA standard

Table B3: Definition of elemental walls for Lisbon according to CEA requisites



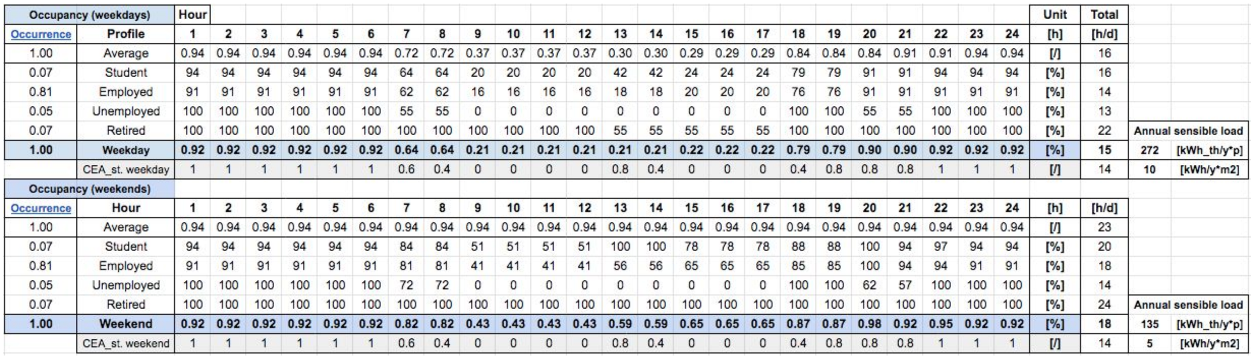
Description	code	U_wall	a_wall	e_wall	r_wall	GHG_WALL_kgCO2m2
Stone wall, 6cm EPS insulation (LNEC_ITE50_II.1B2)	WALL_AS1	2.3	0.6	0.95	0.4	112
Light concrete, no insulation (LNEC_ITE50_II.1A)	WALL_AS2	1.3	0.6	0.95	0.4	112
Concrete, 3cm EPS insulation (LNEC_ITE50_II.2A)	WALL_AS3	0.98	0.6	0.95	0.4	112
Concrete, 4cm XPS insulation (LNEC_ITE50_II.2B1)	WALL_AS4	0.65	0.6	0.95	0.4	112
Concrete, 6cm EPS insulation (LNEC_ITE50_II.2B1)	WALL_AS5	0.55	0.6	0.95	0.4	112
External wall (EPBD Lisbon Standard)	WALL_AS6	0.5	0.6	0.95	0.4	112
Internal partition (EPBD Lisbon Standard)	WALL_AS7	0.8	0.6	0.95	0.4	112
External wall Boavista (CCR 2016)	WALL_AS8	0.44	0.6	0.95	0.4	112
External wall Padre Cruz (CCR 2016)	WALL_AS9	0.4	0.6	0.95	0.4	112

SOURCE	LNEC / Monteiro (2018)	EcoBairros technical sheets
	EPBD requisites	Calculated

Annex C - Use-type/schedule definition

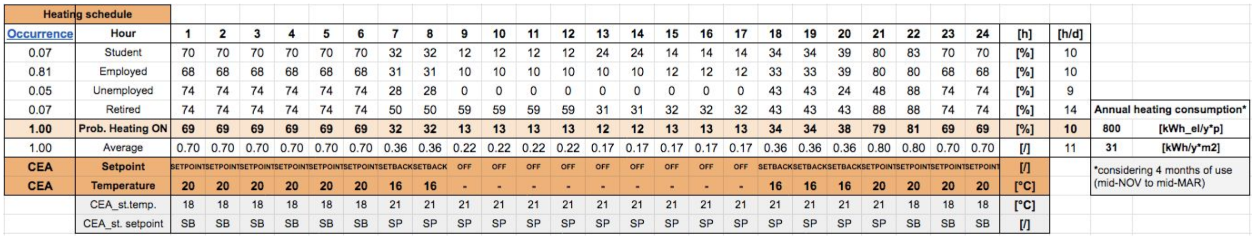
The Annex presents extracts from a spreadsheet in which the schedule of occupancy, heating, appliances and lighting were calculated for each neighbourhood. As an example, Table C1 to Table C3 presents the calculation steps made to define the schedules for an average household of the first income decile in Lisbon (Q1 Lx), developed on the work of Monteiro (2018). Table C4 shows the calculation steps used to characterize the use of appliances for an average Q1 Lx household, which differs significantly from the Portuguese statistics.

Table C1: Definition of occupancy profile for an average household of the first income decile in Lisbon (Q1 Lx), according to the occupancy profiles proposed by Monteiro (2018)



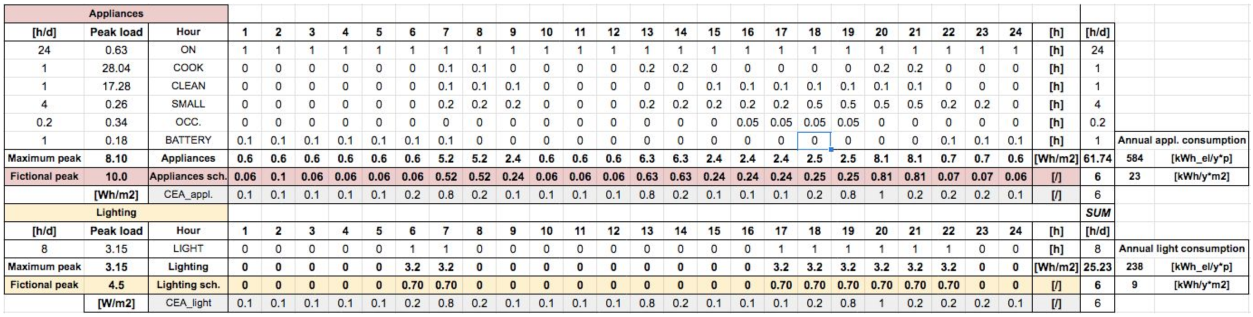
Occupancy (weekdays)		Hour																								Unit	Total		
Occurrence	Profile	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	[h]	[h/d]		
1.00	Average	0.94	0.94	0.94	0.94	0.94	0.94	0.72	0.72	0.37	0.37	0.37	0.37	0.30	0.30	0.29	0.29	0.29	0.84	0.84	0.84	0.91	0.91	0.94	0.94	[/]	16		
0.07	Student	94	94	94	94	94	94	64	64	20	20	20	20	42	42	24	24	24	79	79	91	91	94	94	94	[%]	16		
0.81	Employed	91	91	91	91	91	91	62	62	16	16	16	16	18	18	20	20	20	76	76	91	91	91	91	91	[%]	14		
0.05	Unemployed	100	100	100	100	100	100	55	55	0	0	0	0	0	0	0	0	0	100	100	55	55	100	100	100	[%]	13		
0.07	Retired	100	100	100	100	100	100	100	100	100	100	100	100	55	55	55	55	55	100	100	100	100	100	100	100	[%]	22	Annual sensible load	
1.00	Weekday	0.92	0.92	0.92	0.92	0.92	0.92	0.64	0.64	0.21	0.21	0.21	0.21	0.21	0.21	0.22	0.22	0.22	0.79	0.79	0.90	0.90	0.92	0.92	0.92	[%]	15	272	[kWh_th/y*p]
	CEA_st. weekday	1	1	1	1	1	1	0.6	0.4	0	0	0	0	0.8	0.4	0	0	0	0.4	0.8	0.8	0.8	1	1	1	[/]	14	10	[kWh/y*m2]
Occupancy (weekends)																													
Occurrence	Hour	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	[h]	[h/d]		
1.00	Average	0.94	0.94	0.94	0.94	0.94	0.94	0.94	0.94	0.94	0.94	0.94	0.94	0.94	0.94	0.94	0.94	0.94	0.94	0.94	0.94	0.94	0.94	0.94	0.94	[/]	23		
0.07	Student	94	94	94	94	94	94	84	84	51	51	51	51	100	100	78	78	78	88	88	100	94	97	94	94	[%]	20		
0.81	Employed	91	91	91	91	91	91	81	81	41	41	41	41	56	56	65	65	65	85	85	100	94	94	91	91	[%]	18		
0.05	Unemployed	100	100	100	100	100	100	72	72	0	0	0	0	0	0	0	0	0	100	100	62	57	100	100	100	[%]	14		
0.07	Retired	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	[%]	24	Annual sensible load	
1.00	Weekend	0.92	0.92	0.92	0.92	0.92	0.92	0.82	0.82	0.43	0.43	0.43	0.43	0.59	0.59	0.65	0.65	0.65	0.87	0.87	0.98	0.92	0.95	0.92	0.92	[%]	18	135	[kWh_th/y*p]
	CEA_st. weekend	1	1	1	1	1	1	0.6	0.4	0	0	0	0	0.8	0.4	0	0	0	0.4	0.8	0.8	0.8	1	1	1	[/]	14	5	[kWh/y*m2]

Table C2: Definition of heating use profile for an average household of the first income decile in Lisbon (Q1 Lx), according to the profiles of probability of heating use proposed by Monteiro (2018)



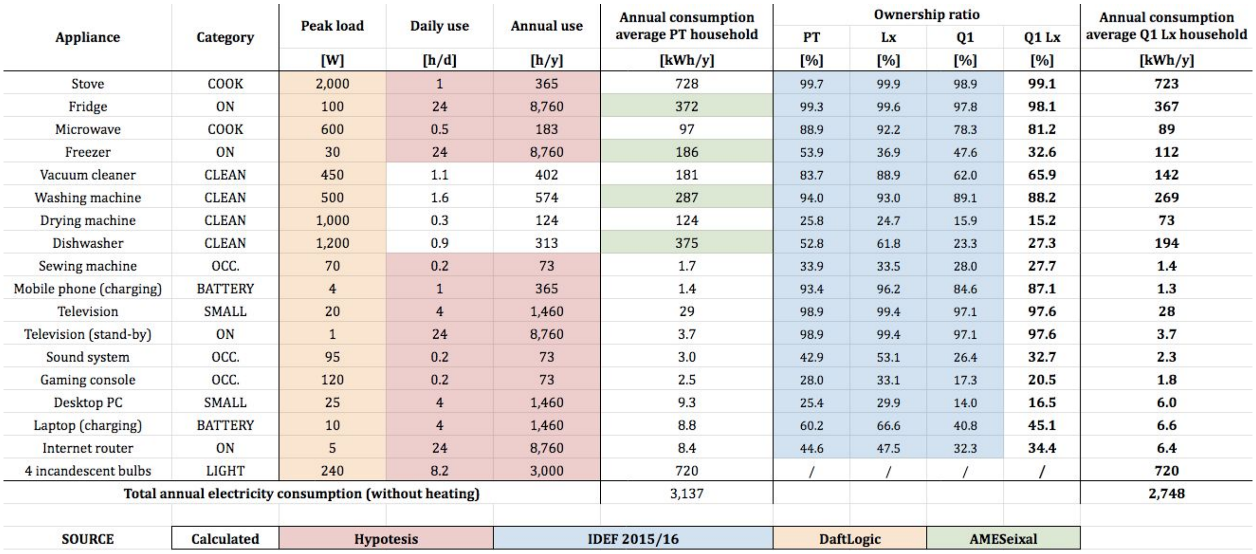
Heating schedule																													
Occurrence	Hour	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	[h]	[h/d]		
0.07	Student	70	70	70	70	70	70	32	32	12	12	12	12	24	24	14	14	14	34	34	39	80	83	70	70	[%]	10		
0.81	Employed	68	68	68	68	68	68	31	31	10	10	10	10	10	10	12	12	12	33	33	39	80	80	68	68	[%]	10		
0.05	Unemployed	74	74	74	74	74	74	28	28	0	0	0	0	0	0	0	0	0	43	43	24	48	88	74	74	[%]	9		
0.07	Retired	74	74	74	74	74	74	50	50	59	59	59	59	31	31	32	32	32	43	43	43	88	88	74	74	[%]	14	Annual heating consumption*	
1.00	Prob. Heating ON	69	69	69	69	69	69	32	32	13	13	13	13	12	12	13	13	13	34	34	38	79	81	69	69	[%]	10	800	[kWh_el/y*p]
1.00	Average	0.70	0.70	0.70	0.70	0.70	0.70	0.36	0.36	0.22	0.22	0.22	0.22	0.17	0.17	0.17	0.17	0.17	0.36	0.36	0.36	0.80	0.80	0.70	0.70	[/]	11	31	[kWh/y*m2]
CEA	Setpoint	SETPOINT	SETPOINT	SETPOINT	SETPOINT	SETPOINT	SETPOINT	SETBACK	SETBACK	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	SETBACK	SETBACK	SETBACK	SETPOINT	SETPOINT	SETPOINT	SETPOINT	[/]		*considering 4 months of use (mid-NOV to mid-MAR)	
CEA	Temperature	20	20	20	20	20	20	16	16	-	-	-	-	-	-	-	-	-	16	16	16	20	20	20	20	[°C]			
	CEA_st.temp.	18	18	18	18	18	18	21	21	21	21	21	21	21	21	21	21	21	21	21	21	21	18	18	18	[°C]			
	CEA_st. setpoint	SB	SB	SB	SB	SB	SB	SP	SP	SP	SP	SP	SP	SP	SP	SP	SP	SP	SP	SP	SP	SP	SB	SB	SB	[/]			

Table C3: Definition of heating use profile for an average household of the first income decile in Lisbon (Q1 Lx), according to the profiles of probability of heating use proposed by Monteiro (2018)



Appliances																														
[h/d]	Peak load	Hour	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	[h]	[h/d]		
24	0.63	ON	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	[h]	24		
1	28.04	COOK	0	0	0	0	0	0	0.1	0.1	0	0	0	0	0.2	0.2	0	0	0	0	0	0.2	0.2	0	0	0	[h]	1		
1	17.28	CLEAN	0	0	0	0	0	0	0.1	0.1	0.1	0	0	0	0	0	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0	0	0	[h]	1		
4	0.26	SMALL	0	0	0	0	0	0	0.2	0.2	0.2	0	0	0	0.2	0.2	0.2	0.2	0.2	0.5	0.5	0.5	0.5	0.2	0.2	0	[h]	4		
0.2	0.34	OCC.	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.05	0.05	0.05	0.05	0	0	0	0	0	[h]	0.2		
1	0.18	BATTERY	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.1	0.1	0.1	[h]	1	Annual appl. consumption	
Maximum peak	8.10	Appliances	0.6	0.6	0.6	0.6	0.6	0.6	5.2	5.2	2.4	0.6	0.6	0.6	6.3	6.3	2.4	2.4	2.4	2.5	2.5	8.1	8.1	0.7	0.7	0.6	[Wh/m2]	61.74	584	[kWh_el/y*p]
Fictional peak	10.0	Appliances sch.	0.06	0.1	0.06	0.06	0.06	0.06	0.52	0.52	0.24	0.06	0.06	0.06	0.63	0.63	0.24	0.24	0.24	0.25	0.25	0.81	0.81	0.07	0.07	0.06	[/]	6	23	[kWh/y*m2]
	[Wh/m2]	CEA_appl.	0.1	0.1	0.1	0.1	0.1	0.2	0.8	0.2	0.1	0.1	0.1	0.1	0.8	0.2	0.1	0.1	0.1	0.2	0.8	1	0.2	0.2	0.2	0.1	[/]	6		
Lighting																												SUM		
[h/d]	Peak load	Hour	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	[h]	[h/d]		
8	3.15	LIGHT	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	0	0	[h]	8	Annual light consumption	
Maximum peak	3.15	Lighting	0	0	0	0	0	3.2	3.2	0	0	0	0	0	0	0	0	0	3.2	3.2	3.2	3.2	3.2	3.2	0	0	[Wh/m2]	25.23	238	[kWh_el/y*p]
Fictional peak	4.5	Lighting sch.	0	0	0	0	0	0.70	0.70	0	0	0	0	0	0	0	0	0	0.70	0.70	0.70	0.70	0.70	0.70	0	0	[/]	6	9	[kWh/y*m2]
	[W/m2]	CEA_light	0.1	0.1	0.1	0.1	0.1	0.2	0.8	0.2	0.1	0.1	0.1	0.1	0.8	0.2	0.1	0.1	0.1	0.2	0.8	1	0.2	0.2	0.2	0.1	[/]	6		

Table C4: Calculation procedure to get the average annual consumption of the most common household's appliances for an average household belonging to the first income quintile of Lisbon (Q1 Lx)



Appliance	Category	Peak load	Daily use	Annual use	Annual consumption average PT household	Ownership ratio				Annual consumption average Q1 Lx household
						PT	Lx	Q1	Q1 Lx	
		[W]	[h/d]	[h/y]	[kWh/y]	[%]	[%]	[%]	[%]	[kWh/y]
Stove	COOK	2,000	1	365	728	99.7	99.9	98.9	**99.1**	**723**
Fridge	ON	100	24	8,760	372	99.3	99.6	97.8	**98.1**	**367**
Microwave	COOK	600	0.5	183	97	88.9	92.2	78.3	**81.2**	**89**
Freezer	ON	30	24	8,760	186	53.9	36.9	47.6	**32.6**	**112**
Vacuum cleaner	CLEAN	450	1.1	402	181	83.7	88.9	62.0	**65.9**	**142**
Washing machine	CLEAN	500	1.6	574	287	94.0	93.0	89.1	**88.2**	**269**
Drying machine	CLEAN	1,000	0.3	124	124	25.8	24.7	15.9	**15.2**	**73**
Dishwasher	CLEAN	1,200	0.9	313	375	52.8	61.8	23.3	**27.3**	**194**
Sewing machine	OCC.	70	0.2	73	1.7	33.9	33.5	28.0	**27.7**	**1.4**
Mobile phone (charging)	BATTERY	4	1	365	1.4	93.4	96.2	84.6	**87.1**	**1.3**
Television	SMALL	20	4	1,460	29	98.9	99.4	97.1	**97.6**	**28**
Television (stand-by)	ON	1	24	8,760	3.7	98.9	99.4	97.1	**97.6**	**3.7**
Sound system	OCC.	95	0.2	73	3.0	42.9	53.1	26.4	**32.7**	**2.3**
Gaming console	OCC.	120	0.2	73	2.5	28.0	33.1	17.3	**20.5**	**1.8**
Desktop PC	SMALL	25	4	1,460	9.3	25.4	29.9	14.0	**16.5**	**6.0**
Laptop (charging)	BATTERY	10	4	1,460	8.8	60.2	66.6	40.8	**45.1**	**6.6**
Internet router	ON	5	24	8,760	8.4	44.6	47.5	32.3	**34.4**	**6.4**
4 incandescent bulbs	LIGHT	240	8.2	3,000	720	/	/	/	/	**720**
Total annual electricity consumption (without heating)					3,137					**2,748**
SOURCE	**Calculated**	**Hypotesis**		**IDEF 2015/16**		**DaftLogic**		**AMESeixal**		

Annex D - CEA metadata structure

The Annex presents one extract from a spreadsheet generated by CEA, in which the structure of the metadata necessary to run the software is presented in detail.

Table D1: “INTRO” sheet of Annex D, which contains the basic structure of CEA metadata

METADATA CEA

databases for City Energy Analyst

Each section contains the description and the structure of the different databases needed for a project with CEA.

/!\ CEA is very case sensitive

Folder	Database		
inputs/building-geometry	zone	▨	🟩
	district	▨	🟩
inputs/building-metering	Conso_Bxxx		🟥
inputs/building-properties	age	▨	🟩
	architecture	🟪	🟧
	indoor_comfort	🟪	🟥
	internal_loads	🟪	🟥
	occupancy	▨	🟩
	restictions	▨	🟧
	supply_systems	▨	🟩
	technical_systems	🟪	🟩
inputs/networks	streets		🟩
inputs/networks/DC \ DH	edges		🟧
	nodes		🟩
inputs/weather/	weather	▨	🟩
inputs/technology/archetypes/	construction_properties	🟦	🟥
	occupancy_schedules	🟦	🟩
	system_controls		🟩
inputs/technology/benchmarks/	benchmark_2000W		🟥
inputs/technology/lifecycle/	LCA_infrastructure	🟦	🟥
	LCA_buildings	🟦	🟥
inputs/technology/systems/	electrical_network		🟥
	electricity_costs		🟩
	emission_systems	🟦	🟥
	envelope_systems	🟦	🟥
	supply_systems		🟥
	thermal_network		🟥
	system_controls		🟥
inputs/technology/uncertainty/	uncertainty_distribution	🟦	🟥

▨ **CEA primary imput data**

🟪 **CEA secondary input data**

🟦 **CEA default databases**

COMPLETE

🟥 **INCOMPLETE**

In the tabs

not yet informed

🟧 maybe incorrect information

Annex E - Neighbourhood maps

The Annex presents some examples of the geographical distribution of energy consumption and of the prevalence of thermal comfort and discomfort caused by cold conditions, before and after the implementation of the retrofit activities (described in chapter 3.3), for three neighbourhoods representative of the variety of conditions found in the case study area (Alfredo Bensaúde, Bairro do Boavista & Quinta dos Ourives).

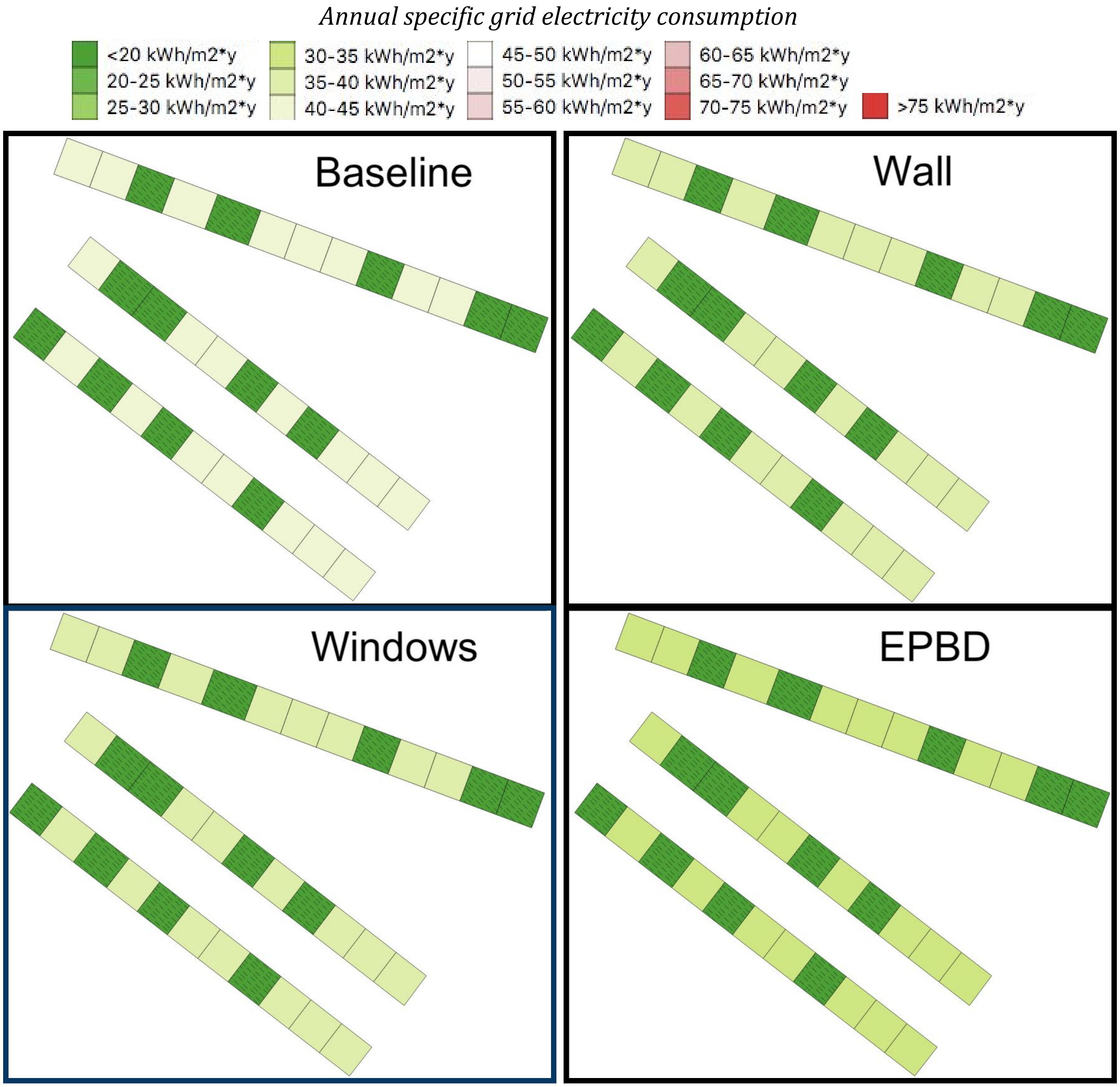


Figure E1: Spatial distribution of specific grid electricity consumption (EL - $\frac{kWh}{y \cdot m^2}$) in Alfredo Bensaúde, at the current stat (Baseline - top left) and after the implementation of the Wall (top right), Windows (bottom left) and EPBD (bottom right) retrofits; the buildings considered lacking a heating system are marked by diagonal dashed lines

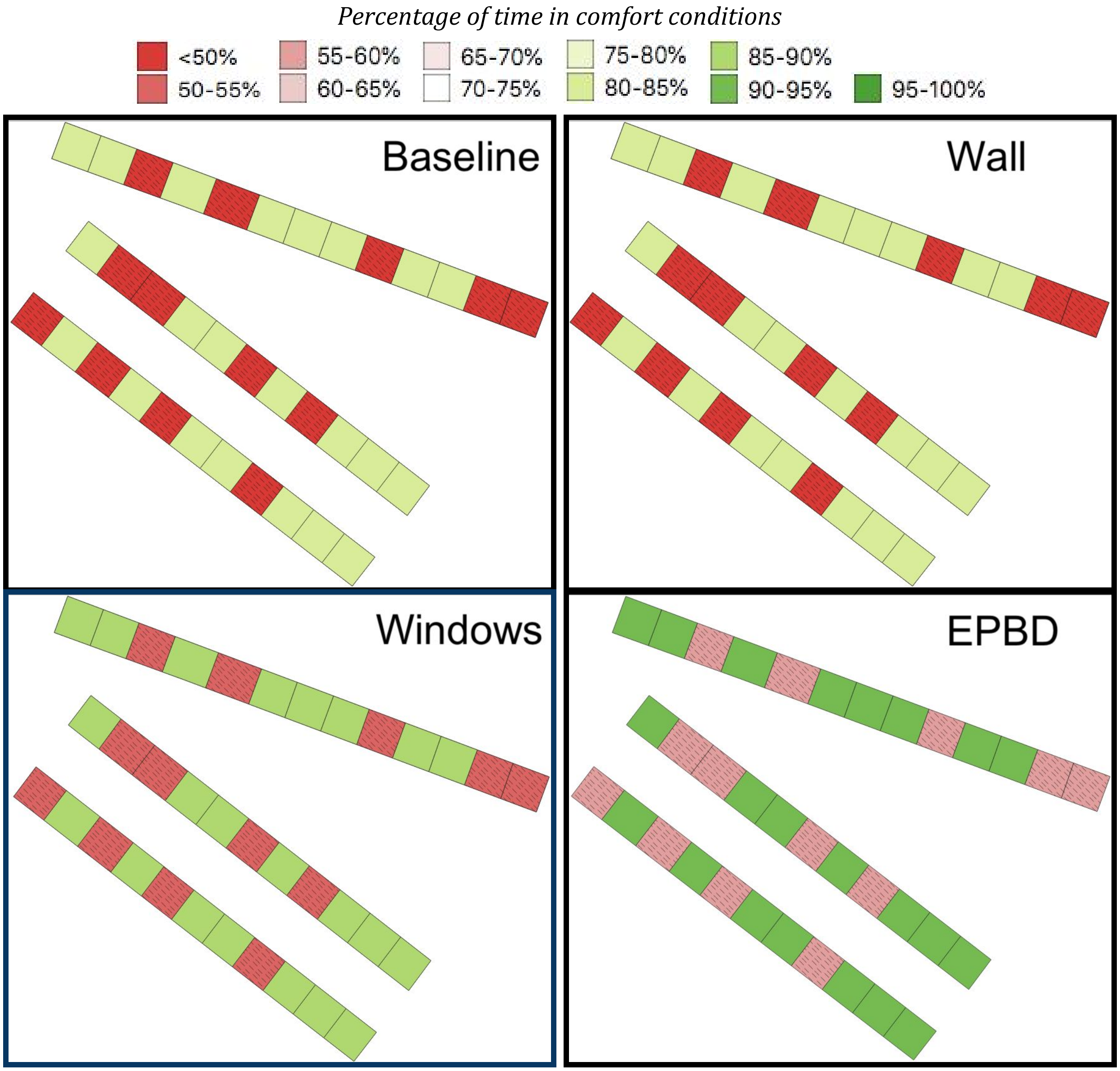


Figure E2: Prevalence of thermal comfort (green) and discomfort (red) conditions in Alfredo Bensaúde, at the current state (Baseline - top left) and after the implementation of the Wall (top right), Windows (bottom left) and EPBD (bottom right) retrofits; the buildings considered lacking a heating system are marked by diagonal dashed lines

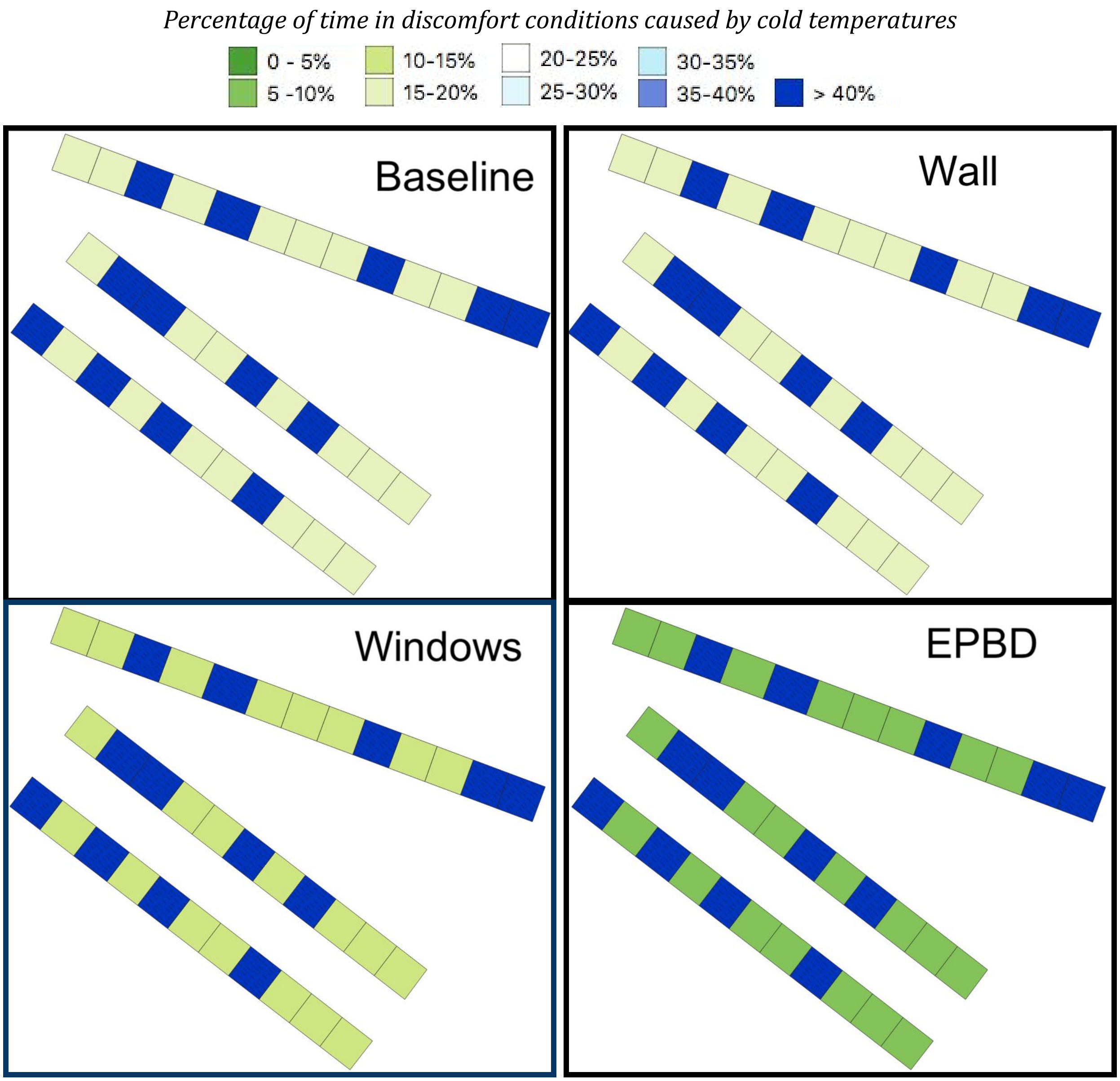


Figure E3: Prevalence of thermal discomfort due to cold conditions (blue) in Alfredo Bensaúde, at the current state (Baseline - top left) and after the implementation of the Wall (top right), Windows (bottom left) and EPBD (bottom right) retrofits; the buildings considered lacking a heating system are marked by diagonal dashed lines

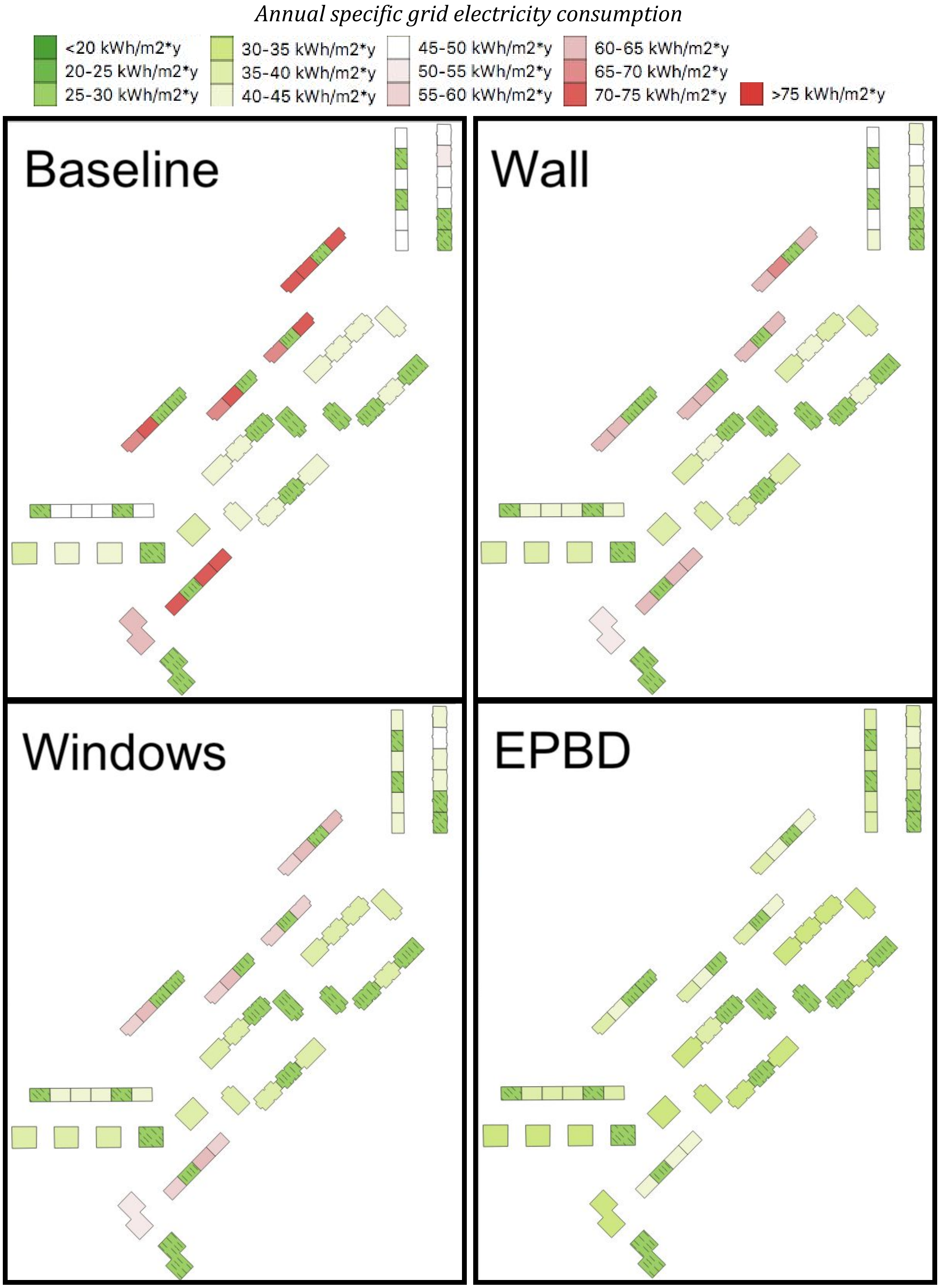


Figure E4: Spatial distribution of specific grid electricity consumption (EL - $\frac{kWh}{y \cdot m^2}$) in Bairro do Boavista, at the current state (Baseline - top left) and after the implementation of the Wall (top right), Windows (bottom left) and EPBD (bottom right) retrofits; the buildings of standard 1 are not included; the buildings considered lacking a heating system are marked by diagonal dashed lines

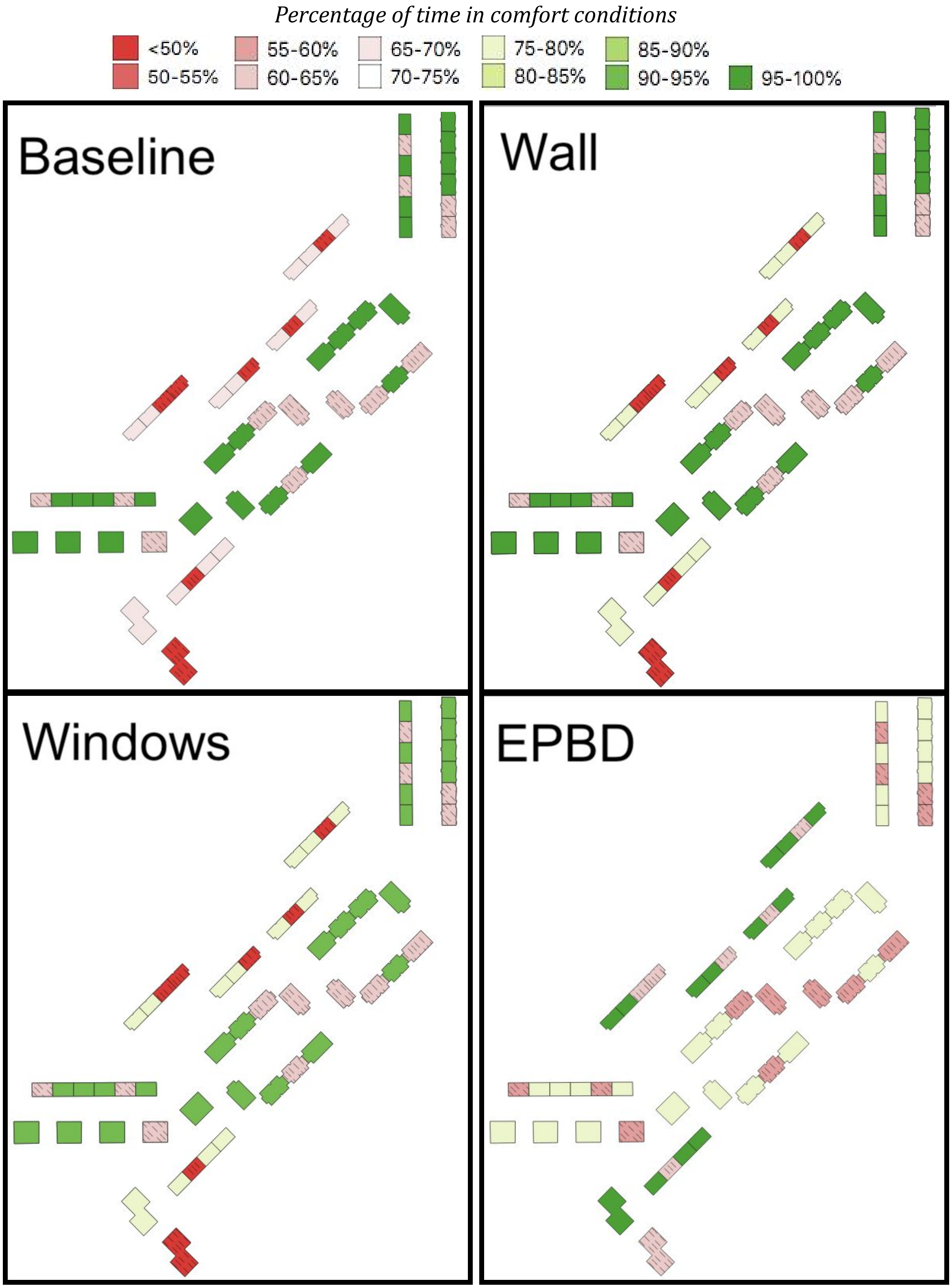


Figure E5: Prevalence of thermal comfort (green) and discomfort (red) conditions in Bairro do Boavista, at the current state (Baseline - top left) and after the implementation of the Wall (top right), Windows (bottom left) and EPBD (bottom right) retrofits; the buildings of standard 1 are not included; the buildings considered lacking a heating system are marked by diagonal dashed lines

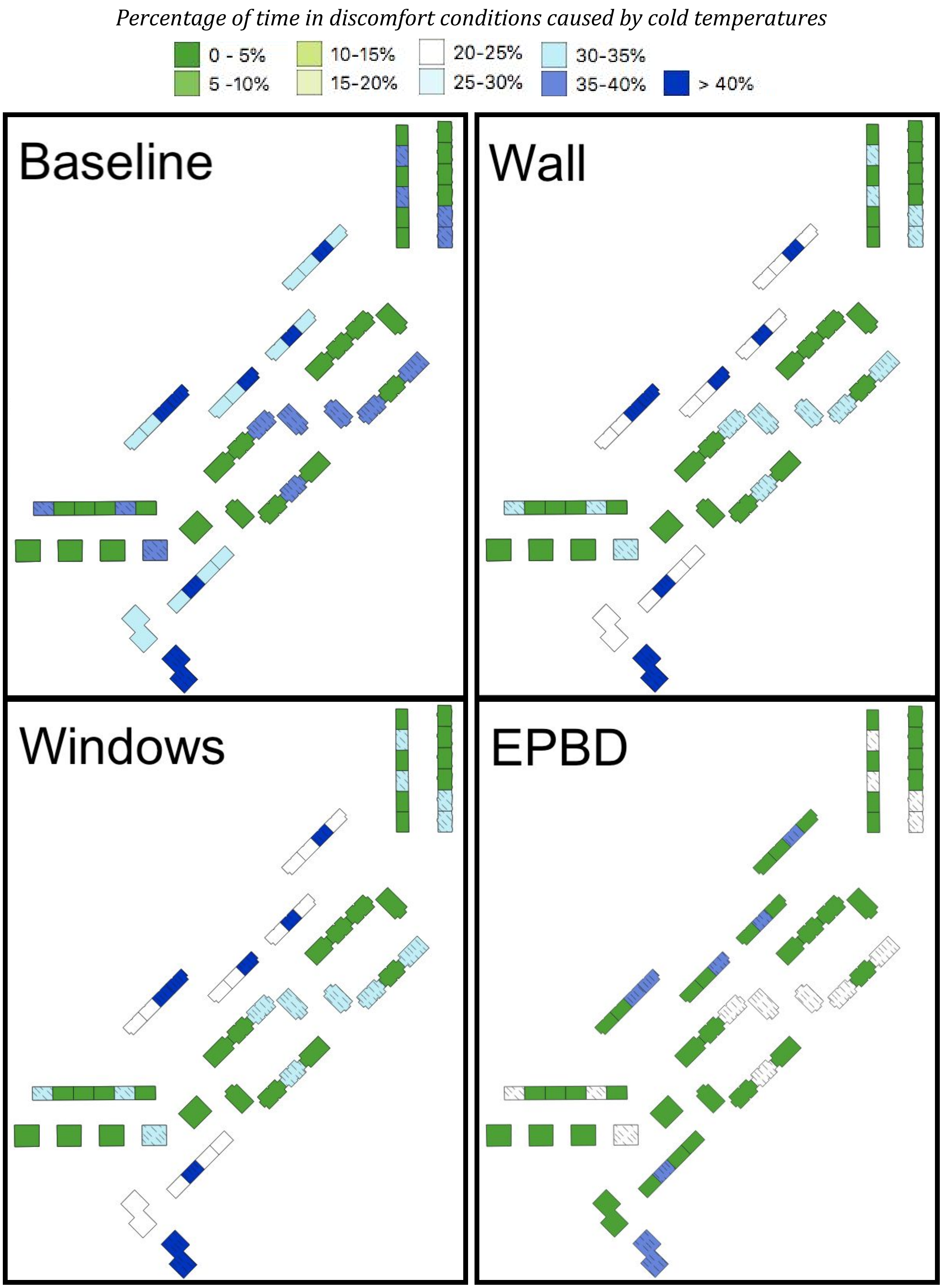

Percentage of time in discomfort conditions caused by cold temperatures

Figure E6: Prevalence of thermal discomfort due to cold conditions (blue) in Bairro do Boavista, at the current state (Baseline - top left) and after the implementation of the Wall (top right), Windows (bottom left) and EPBD (bottom right) retrofits; the buildings of standard 1 are not included; the buildings considered lacking a heating system are marked by diagonal dashed lines

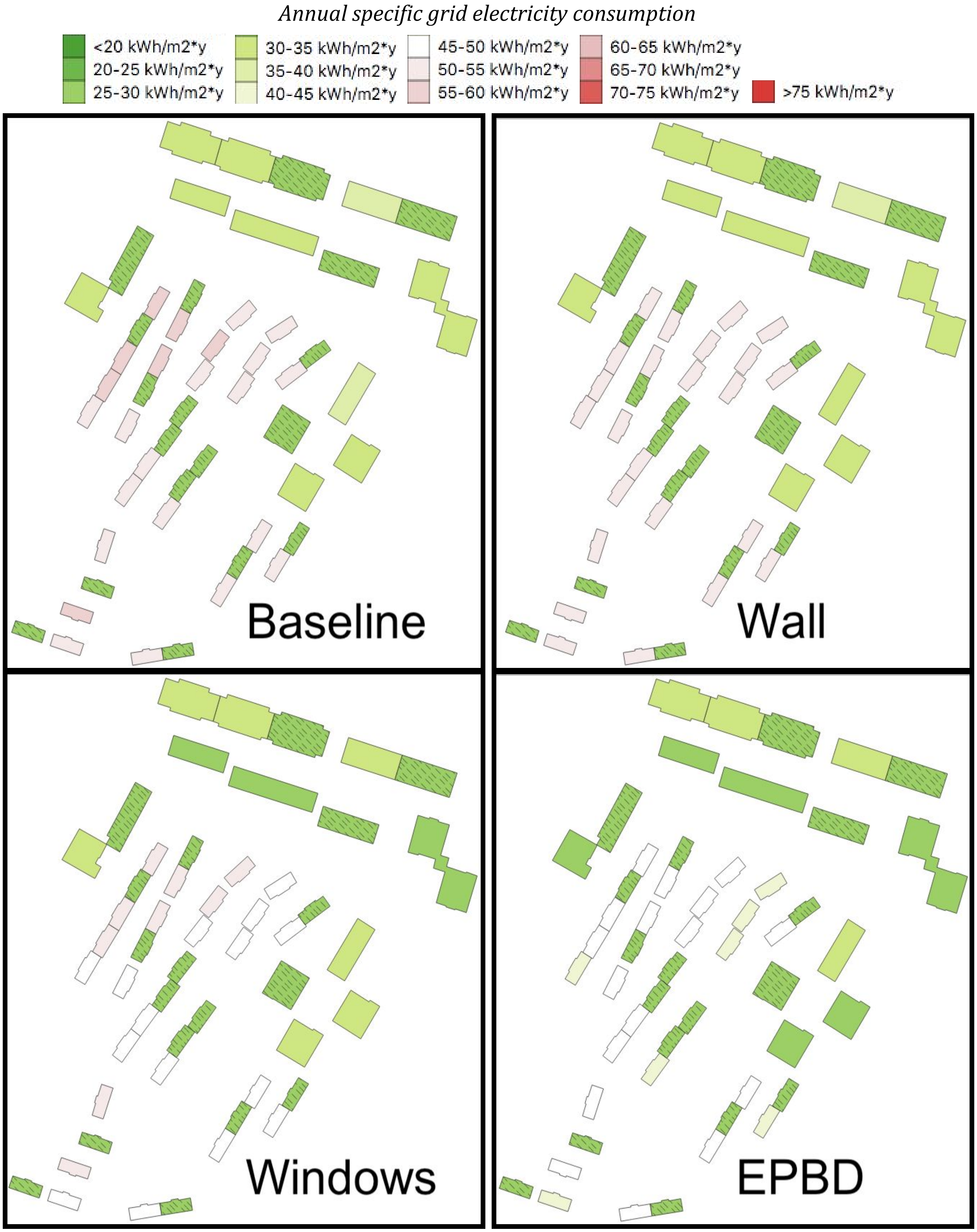


Figure E7: Spatial distribution of specific grid electricity consumption (EL - $\frac{kWh}{y \cdot m^2}$) in Quinta dos Ourives, at the current state (Baseline - top left) and after the implementation of the Wall (top right), Windows (bottom left) and EPBD (bottom right) retrofits; the buildings considered lacking a heating system are marked by diagonal dashed lines

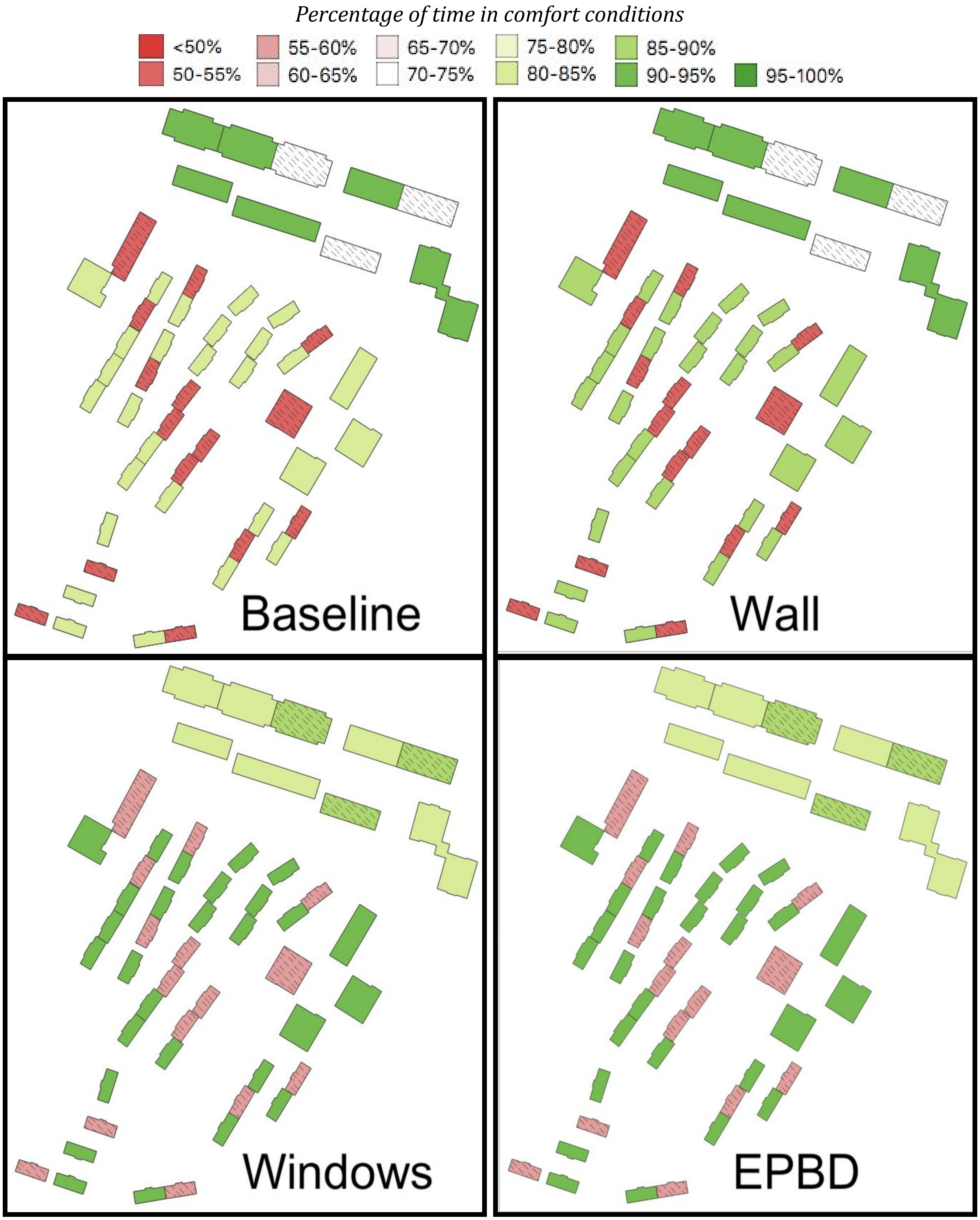


Figure E8: Prevalence of thermal comfort (green) and discomfort (red) conditions in Quinta dos Ourives, at the current state (Baseline - top left) and after the implementation of the Wall (top right), Windows (bottom left) and EPBD (bottom right) retrofits; the buildings considered lacking a heating system are marked by diagonal dashed lines

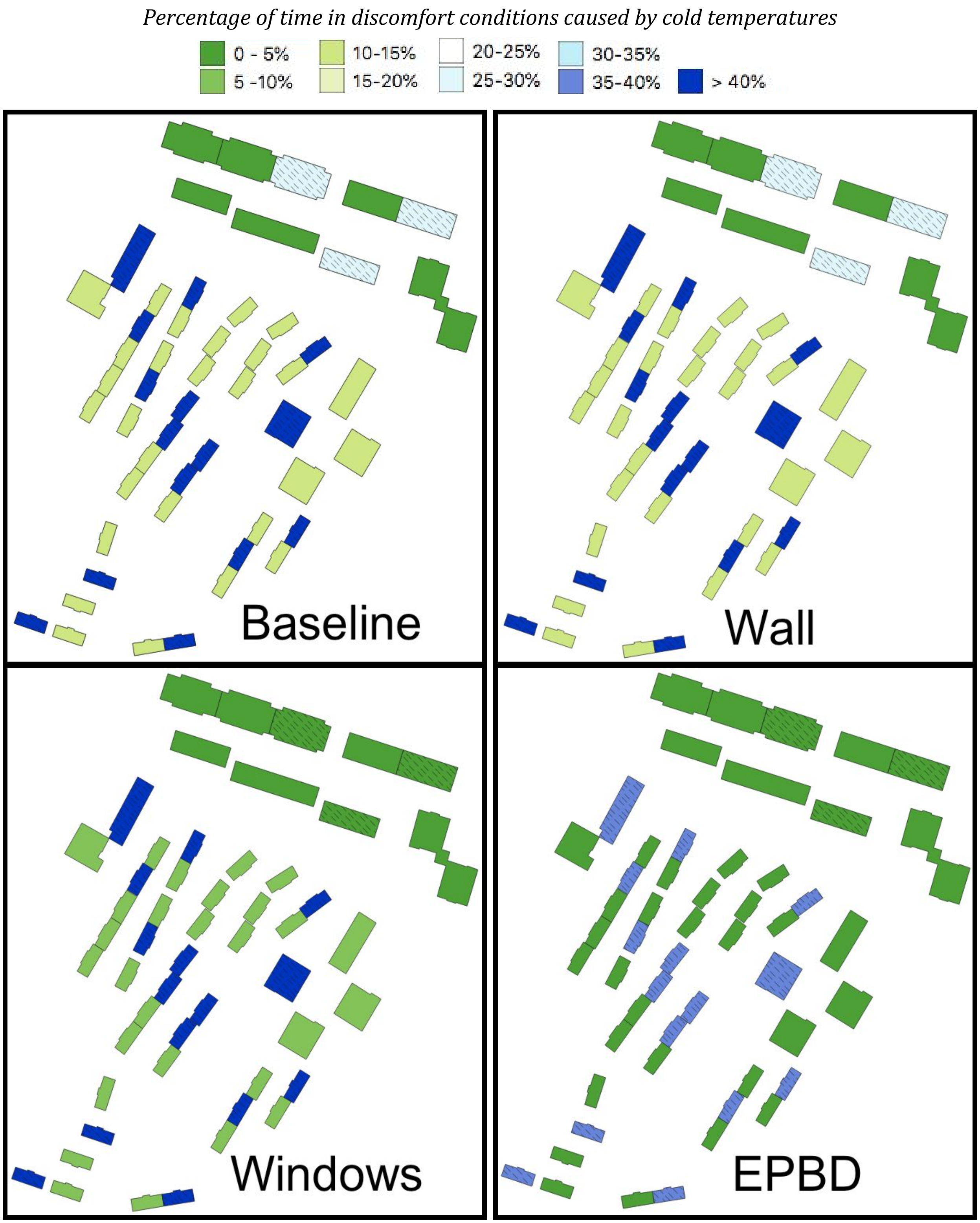


Figure E9: Prevalence of thermal discomfort due to cold conditions (blue) in Quinta dos Ourives,, at the current state (Baseline - top left) and after the implementation of the Wall (top right), Windows (bottom left) and EPBD (bottom right) retrofits; the buildings considered lacking a heating system are marked by diagonal dashed lines