LIFE-CYCLE ENERGY IN HOUSES: SEARCHING LOW ENERGY HOUSES OPERATION. CASE STUDY OF GREEN VALLEY, LISBON

Diana Ionescu

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Energy Engineering and Management

Supervisor: Prof. Manuel Guilherme Caras Altas Duarte Pinheiro

Examination Committee

Chairperson: Prof. Luís Filipe Moreira Mendes

Supervisor: Prof. Manuel Guilherme Caras Altas Duarte Pinheiro

Member of the Committee: Prof. Carlos Augusto Santos Silva

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Resumo

Nos últimos anos, tem-se prestado cada vez mais atenção ao impacto ambiental da produção e uso de energia, devido ao aumento da população, à procura de energia e, implicitamente, à diminuição dos recursos e e também às alterações climatéricas. Como o setor de construção consome 40% da energia final na Europa, a União Europeia encontrar-se a fazer um esforço para mitigar esta situação por meio de um quadro legislativo. Consistindo em 80-90% da procura total de energia de uma habitação residencial, Energia Operacional, definida como a energia consumida por um edifício durante sua vida útil (para aquecimento, arrefecimento, ventilação, iluminação, eletrodomésticos e água quente sanitária), é o foco principal para reduzir a procura de energia residencial.

A hipótese desta tese é que a energia operacional num edifício pode ser reduzida mesmo num edifício que já seja altamente eficiente (Edifício de Baixa Energia ou Energia Zero).

Por esta razão, um case de estudo foi selecionado para análise, ou seja, uma moradia unifamiliar com dois pisos acima do solo e um piso subterrâneo para estacionamento e sistemas técnicos, com uma superfície útil de 353 m2. Já classificado como um edifício A + e A ++ em energia operacional de acordo com as certificações LiderA, o edifício consome 21,010 kWh / ano para iluminação e uso de eletrodomésticos, e 3,396 kWh / ano para produção de AQS . Um modelo Excel foi desenvolvido para comparar os consumos especificados no certificado com valores mais concretos e, então, foi usado para simular vários cenários de melhoria, a fim de reduzir ainda mais a carga de energia e o carbono operacional. Como o prédio já é altamente eficiente, três cenários básicos foram desenvolvidos, garantindo que toda a iluminação seja feita com LEDs, instalação adicional de coletor solar e instalação fotovoltaica adicional. Os cenários foram então combinados para observar as poupanças globais, bem como o investimento necessário para obter essas poupanças. Foi determinado que até 3,524 kWh por ano poderiam ser economizados com investimentos razoáveis.

Palavras-chave: Energia Operacional, Energia do Ciclo de Vida, Economia de Energia, Ambiente Construído

Abstract

In the recent years, more and more attention has been paid to the environmental impact of energy production and use, due to the increase in population, energy demand and, implicitly, dwindling resources as well as noticeable climate changes. As the building sector consumes 40% of the final energy in Europe, the European Union is making an effort to reduce this by means of legislative framework. Consisting of as much as 80-90% of the total energy demand of a household, Operational Energy, defined as the energy consumed by a building during its lifetime (for heating, cooling, ventilation, lighting, appliances and domestic hot water purposes), is the main focus for reducing the residential energy demand.

The hypothesis of this thesis is that operational energy in a building can be reduced even in a highly efficient building (Low Energy or Nearly Zero Energy Building).

For this reason, a case study has been selected for analysis, namely a single-family townhouse with two floors above ground and an underground floor for parking and technical systems, with a useful surface of 353 m^2. Already classified as an A+ building and A++ regarding operational energy according to LiderA certifications, the building consumes 21,010 kWh/year for lighting and appliance use and 3,396 kWh/year for DHW production. An Excel model has been developed in order to compare the consumptions specified in the certificate with more concrete values and was then used to simulate various improvement scenarios in order to reduce the energy load and operational carbon even further. Since the building is already highly efficient, three base scenarios were developed, ensuring that all lighting is done with LEDs, additional solar collector installation, and additional PV installation. The scenarios were then combined to observe the overall savings, as well as the investment required in order to obtain said savings. It was determined that up to 3,524 kWh per year could be saved with reasonable investments.

Key words: Operational Energy, Life Cycle Energy, Energy Savings, Built Environment

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Nomenclature

BER	Building Energy Rating
CDD	Cooling Degree Day
CO_2	Carbon Dioxide
COP	Performance Coefficient
DHW	Domestic Hot Water
EE	Embodied Energy
EED	Energy Efficiency Directive
EPBD	Energy Performance of Buildings Directive
EV	Electric Vehicle
GHG	Greenhouse Gas
HDD	Heating Degree Day
HVAC	Heating, Ventilation and Air Conditioning
IEA	International Energy Agency
JRC	Joint Research Centre
LCE	Life Cycle Energy
LED	Light-Emitting Diode
LEB	Low Energy Building
MPP	Maximum Power Point
NG	Natural Gas
NOCT	Normal Operating Cell Temperature
nZEB	Nearly Zero Energy Building
OE	Operational Energy
PED	Primary Energy Demand
PV	Photovoltaic
RED	Renewable Energy Directive
RES	Renewable Energy System(s)
TPES	Total Primary Energy Supply

1. Introduction

1.1. Thesis motivation

Due to recent concerns regarding the environmental impact of energy production and use, increasing attention is paid to the causes and management of these observed problems. This has led the European Union (EU) to become particularly interested in the reduction of energy generation from fossil fuels by means of implementing renewable energy systems, as well as by promoting energy efficiency in its most demanding sectors. In particular, through the Directive 2010/31/EU, the European Union has set the goal to reduce its energy consumption by 20% by the year 2020, as well as to cover 20% of said consumption from renewable energy sources by the same deadline [1]. Said directive was further added upon through the 2012 Directive on Energy Efficiency [2] which proposed an improvement of 30% in energy efficiency by 2030; this value was extended to 40% in 2015, to be completed by the same deadline.

Consuming 40 % of final energy in Europe [3], the building sector is an important area of focus due to its potential for energy efficiency improvements, which can be done both at the construction phase by means of better insulating materials for instance, as well as in the operation phase by implementing more efficient appliances and using renewable systems for energy production. Awareness of these possibilities has spread rapidly in recent years, leading to the appearance of legislative framework to support improvement of energy efficiency in buildings by means of:

- The **Energy Performance of Buildings Directive (EPBD)** [3], which focuses on defining energy performance requirements for buildings (whether new or renovated) and building elements, as well as establishing inspection schemes for heating and cooling systems, and elaborating performance certificates that need to be included when advertising a building.
- The **Energy Efficiency Directive (EED)** [3], which states that EU countries need to define long-term renovation strategies for buildings, as well as purchase only buildings which are classified as highly energy efficient. Moreover, a minimum of 3% of the buildings owned or occupied by the government must be renovated in order to become more efficient.
- The **Renewable Energy Directive (RED)** [4], which states that at least 20% of the energy production in Europe must be obtained by means of renewable energy systems.

According to Dracou et al. (2017) [5], the target of the 2010/31/UE Directive is *'achievable if a majority of the energy used in the buildings comes from renewable energy technologies and if the regulated loads of the buildings are reduced through the use of energy conservation technologies'*. Moreover, the study gives the average yearly consumption of European buildings as varying between 70 and 230 kWh/m^2 per year.

In terms of consumption, the buildings sector is thought to require:

- Almost "*40% of the raw materials consumption"*, "*40% of global energy consumption"*, "*25% of solid waste and water use*", "*12% of land use*" and "*about 33% of GHG emissions*" according to Huang et al. (2017) [6].
- *"30-40% of all primary energy"* [7].

1.2. Problem definition and importance

1.2.1. Issue

As it has been defined by the European Union itself, the energy consumption in the built environment is a critical issue to tackle, especially if one considers the current population expansion, which will also lead to more residential areas being required. This means that, should energy efficient measures not be implemented, the energy requirements will inevitably increase as well. Therefore, it is important to assess the main components of a building that influence the energy consumption, and to look into energy efficient alternatives or passive measures where possible.

The case study chosen for analysis, a townhouse located in Lisbon, Portugal, has already been certified as a class A+ building according to LiderA standards, and even A++ regarding operational energy requirements. For this reason, analyzing an already highly efficient building for even further possible, affordable and easy to implement improvements is an interesting task to undertake. Furthermore, the approach used in the analysis is one that is both thorough and easy to follow, which can lead to the calculation model having the possibility of being applied even by people who do not hold a specific degree of knowledge on the topic of energy and more specifically, renewable energy systems.

1.2.2. Location

Located in the Iberian Peninsula, Portugal allegedly has one of the lowest shares of energy consumption for space heating (21.4% of end-use energy consumption in households) [8]. Also, by averaging 2,500 to 3,200 hours of sunlight per year [9], the country has tremendous potential for applications of renewable energy such as photovoltaic (PV) panels and solar thermal collectors. This is particularly noticeable in European statistics, where Portugal has the largest share of renewable energy use for building heating purposes (73%) [8]. However, one aspect which is often overlooked is the fact that it is easy to cover the majority of heating demand from renewables if not many buildings have a heating system in place. Indeed, many residents of Portugal do not often see the purpose of investing in it, since winters are generally milder than on the rest of the continent. For this reason, a study commissioned by Quercus found that 21% of responders relied only on heaters, 37% claimed to have no insulation in the building, and 35% were unsure whether their homes were insulated or not [10].

For this reason, it can be said that while Portugal does indeed have the high potential for energy production from photovoltaics and solar collectors, there is a difference between this and the thermal comfort being achieved for its residents. As the household sector accounts for 17% of the total energy consumption of the country [11], it becomes important to analyze the methods by which energy consumption can be reduced in this sector.

1.3. Hypothesis, objectives and methodology

1.3.1. Hypothesis and objective

The hypothesis of this thesis is that operational energy in the building life cycle can be reduced, even for low energy and even nearly zero energy buildings. Moreover, this reduction is thought to have potential for economic feasibility as well.

As a result, the objective of the thesis is to analyze a chosen case study in terms of operational energy parameters, which will be modelled into an Excel application and tested to observe how theoretical and practical values vary from one another. Emphasis will be placed on performing this analysis in terms of economic feasibility and environmental sustainability in order to reduce the energy demand during the building life-cycle.

1.3.2. Methodology

The main steps which will be undertaken in this analysis are:

1. **Review of operational energy state-of-the-art and identification of operational energy sources and results**

   In this chapter, the thesis will begin by defining the main terms which will form the basis of this analysis, namely Nearly Zero Energy Buildings (nZEB) and Operational Energy (OE). Upon clearly defining said terms, a state-of-the-art will be conducted in order to research the consumption of similar dwellings.

2. **Excel modelling**

   For the model, the main characteristics of the building, such as lighting, appliances and domestic hot water (DHW) production systems, will be analyzed to determine their specific energy consumption for the current status. The model will generate the operational energy parameters, such as energy consumption and emissions based on input values.

   The Excel model will be elaborated in such a way as to allow for easy modification of specific parameters of the building. Several alternatives will be then incorporated one at a time to assess their influence on the energy consumption and carbon emissions, in terms of investment versus environmental impact reduced.

3. **Case study analysis**

   This part of the thesis will involve the study of a chosen building in Lisbon, Portugal, which is defined as a Class A building by Energy Performance Certification, and as a Class A+ building by LiderA Certification. Various aspects of operational energy, such as heating, cooling, ventilation, lighting and hot water production parameters will be analyzed in order to determine their impact on the overall energy demand of the selected building. An analysis between obtained results and expected performance will also be conducted.

   Initially, an analysis of the current status of the selected location will be conducted, in order to determine the energy requirements with the existing conditions. For this, data will be obtained regarding the appliances present in the building, and additional data from the study visit will also be incorporated in the analysis. In the end, the following parameters can be determined:

- Yearly lighting consumption;
- Yearly appliance consumption;
- Yearly DHW requirements.

Note: Due to the special characteristics of the building, which shall be discussed further in Subchapter **3.3 LiderA Certification**, as well as the necessity of analyzing the case study from a construction materials point of view, the yearly heating and cooling demands will be collected from the energy certificate of the building and used accordingly.

Based on these values, an initial determination of CO_2 emissions will be carried out by assuming no renewable energy generation for the chosen location.

Further, the present RES installed will be analyzed in terms of their yearly energy generation:

- PV panels will be analyzed in terms of the yearly electricity generation;
- Solar collectors will be analyzed in terms of yearly energy yield for DHW production;

The analysis of PV and collector yield will be carried out by using local solar irradiation values, as well as the specifications of the particular models used in the location. By eliminating the share of energy covered by renewables from the calculations, the remaining energy will be assumed to be covered by using electricity from the grid, and the environmental impact will be once again assessed.

4. Results discussion and improvement proposal

Based on the analysis performed in the previous chapter, relevant conclusions will be drawn in terms of actual building performance and the impact of operational energy. For each of the parameters, several alternatives from the literature review performed will then be explored to define the most beneficial solution in terms of energy efficiency, lifetime and economy.

5. Conclusion

Based on the initial and subsequent determinations conducted by using the Excel model, conclusions will be drawn in terms of the importance of operational energy in the life-cycle of buildings, as well as the potential for improvements and reduction of energy consumption. The potential of OE to contribute to buildings being classified as nZEBs will also be discussed, in relation to energy savings, investment and cost benefits.

2. State-of-the-art

2.1. Nearly Zero Energy Buildings (nZEBs)

In accordance to the EPBD, an nZEB means *'a building that has a very high energy performance, as determined in accordance with Annex 1. The nearly zero or very low amount of energy required should be covered to a very significant extent by energy from renewable sources, including energy from renewable sources produced on-site or nearby'* [12]. The EPBD also states that *'the energy performance of a building shall be expressed in a transparent manner and shall include an energy performance indicator and a numeric indicator of primary energy use'* [12]. Moreover, their construction and operation allow for their energy consumption to decrease over time and in time it can be matched by the energy supplied from renewables [5] (Figure 1).

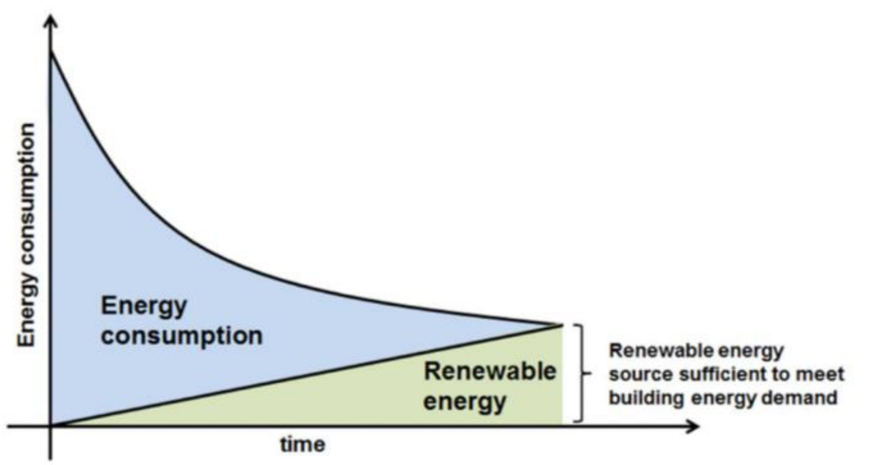


Figure 1. nZEB concept definition [5]

However, at present, there is no consistent definition of nZEB given in a defined manner for Portugal. According to a study analyzing 7 southern countries [12], while Portugal currently has a National Plan in place, it does not give any numeric indicators in actual values, but rather dependent on variables such as *'technical viability, climate, type of construction, traditions, etc.'*

Among the general issues identified regarding nZEB definition in Southern countries in the same study [12], the following were found to be the among the main causes:

a) Due to their position, Southern countries require higher loads for heating in winter and cooling in summer. Therefore, both heating and cooling systems need to be installed.

b) The *'overheating phenomena'* in Southern Europe leads to modifications in **thermal comfort limits** and is generally attributed to some general parameters without accounting for others which may serve to provide passive cooling (*'presence or lack of solar protections', 'outdoor air in summer nights',* etc).

c) There is a preference towards installing many renewable energy systems (RES), without the same regard for investing in energy efficiency. This can be problematic as in some urban areas PV access or biomass burning are not viable alternatives.

For the specific case of Portugal, whilst their regulations have been adapted based on the EPBD and now define nZEB as *'a building that uses the cost-optimal solutions for the envelope and where the renewable energy harvested on-site or nearby is used to fulfill a significant part of the remaining energy needs'*, this definition is not yet complete and does not specify any requirements regarding renovation and rehabilitation towards nZEB standards [12]. The study also describes the required share of renewable energy systems to be installed locally in order for a building to be classified as nZEB, as 50% in the overall energy demand of the building.

2.2. Building Life Cycle

The life cycle of a building is typically composed of the following processes:

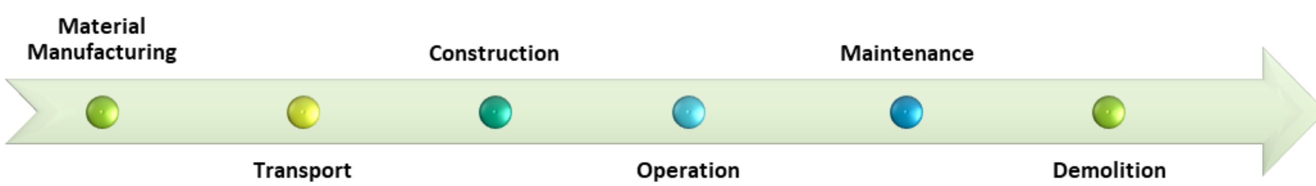


Figure 2. Building life cycle [13]

Of the processes, operational energy related emissions are *'regarded as the largest contributor to the life-cycle impacts'* [13], and can be significantly reduced by applying energy efficiency methods. Operational emissions are defined as emissions related to heating, cooling, ventilation, lighting and appliance use [13].

2.3. Operational Energy

Based on recent legislation, all new buildings shall require an Energy Performance Certificate (EPC) in order to be sold or rented, where the EPC refers to the amount of energy required for the building's standard needs (heating, cooling, ventilation and lighting). This is generally determined based on the occupancy of the building [14].

According to a customer survey conducted in 2010 [15], household energy consumption in Portugal was divided as follows:

- 10.7 % for space heating;
- 0.7 % for space cooling;
- 27.6 % for water heating;
- 6.1 % for lighting
- 14.9 % for electrical appliances;
- 40.0 % for kitchen appliances.

Operational energy (OE) refers to the amount of primary energy that a building consumes over its lifetime, in other words the *'Primary Energy Demand (PED) for heating, ventilation, cooling, hot water production and lighting'* [14]. The values are measured as energy per unit conditioned floor area, or kWh/m^2/year, and can amount to as much as 80-90% *'in conventional buildings and 40-60% in low energy buildings'* [6].

Moreover, it was determined in a study carried out by Iddon and Firth (2013) [16] that operational carbon is able to account for as much as *'74-80% of carbon emissions over a 60-year lifespan of dwellings'*, around 70% of which can be attributed to space heating.

Due to the high share of appliances' consumption in the overall energy requirements of a building, this thesis will use an adapted version of the aforementioned definition and include this consumption as well. Operational energy will therefore be defined as the energy demand of a building for the duration of its lifetime for the purposes of heating, cooling, ventilation, hot water production, lighting and electrical appliances use.

2.4. Parameters that influence OE

By analyzing operational energy and the factors which have a hand in modifying its values, the following parameters have been identified as being of interest [6]:

a) Shape and orientation of building
b) Thermal properties of construction and envelope materials
c) Shading
d) Surrounding environment
e) Climate
f) Occupant behavior
g) Window glazing

Of these, a study conducted by Pacheco et al. (2012) [17] identified orientation, shape, and ratio of external surface and volume of the building as being the most influential.

Occupant behavior is another highly important parameter, as it influences the time periods during which electric equipment use, space heating and cooling, ventilation and hot water consumption take place. The occupants' way of life and social standing also influence the affordability of equipment and energy bills, and therefore their attitude towards energy consumption. Comfort parameters also serve to vary energy consumption depending on location due to climate and personal comfort requirements.

A study by Bourgeois et al. (2006) [18] further found that *'occupants that actively seek natural daylight rather than relying on artificial lighting can save more than 40% on their overall primary energy expenditure'* (as taken from [6]).

The location selected for the analysis is another factor which needs to be considered, as connections have been found between their *"level of income and development"* and the "*energy consumption and carbon emissions"* [19].

Based on a conducted study by Giordano et al. (2015) [14], it was also determined that the values of embodied energy increase when energy-intensive materials are used in construction, whereas operational energy determination depends on solar gain, shadowing factor and heat transmission.

2.5. LiderA

LiderA is defined as *'a Sustainable Evaluation System which can be used to search for sustainability in plans or projects and be applied to urban environments or buildings, allowing them to be certified or recognized by the system's brand'* [20].

The system works with 6 main principle: Site and Mitigation, Resources, Environmental Loadings, Environmental Comfort, Socio-Economic Aspects and Sustainable Use. These are further split into a total of 22 areas and 43 criteria. The criteria themselves each present various performance levels between 0-10 and maybe even higher on occasion, as well as a numerical assessment. Both can then be converted into a class from G to A++ (Figure 3).

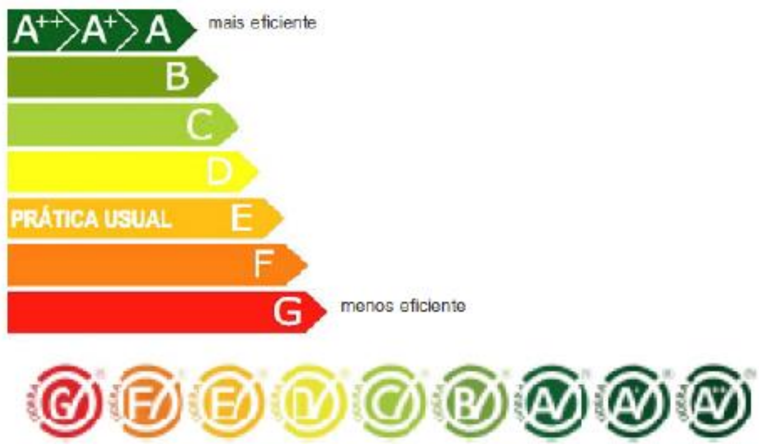


Figure 3. LiderA specification levels [20]

The building performances can be classified as follows (Table 1):

Table 1. LiderA classification definitions

Classification	Description
Class E	Common practice
Class D	Improvement of 12.5%
Class C	Improvement of 25%
Class B	Improvement of 37.5%
Class A	Improvement of 50%
Class A +	Improvement of 75% or Factor 4 improvement
Class A ++	Improvement of 90% or Factor 10 improvement

2.6. Literature review

An analysis was conducted to determine the main value for the consumption of various components of the OE, as well as the environmental impact of operational energy and its overall share in the consumption of a building. Initially, a total of 64 journal articles and studies were looked into (2 of which from Portugal), and were analyzed on the following parameters:

- Location
- Year
- Number of and types of buildings analyzed (dwelling, apartment, non-residential)
- Material used for building
- Building surface
- Number of floors
- Number of inhabitants
- Software used
- Lifetime considered
- OE components consumption (HVAC, lighting, DHW, appliances)
- Lifetime consumption
- Share of OE in lifetime consumption
- Emissions related to the OE

The articles were then narrowed down to those discussing only houses, therefore removing non-residential and apartment buildings, and the parameters pertaining to the remaining ones were summarized in Table 2, Table 3, Table 4 and Table 5, summing a total of 45 case studies. Based on these, the following observations can be made:

- Lower heating requirements were observed by Adalberth (1997) [21] for a building consisting of two floors rather than one, due to the lower transmission losses and air change rate;
- Blanchard & Reppe (1999) [22] analyzed several OE reduction methods, and the following were more noteworthy:
    - Energy efficient appliance use was found to reduce the annual electricity consumption by as much as 40%.
    - Natural gas appliances were implemented where possible.

    - Replacement of incandescent lightbulbs with more efficient compact and fluorescent lightbulbs was found to reduce as much as 686 kWh/year.
    - Reduction in OE was also observed by improving on the building envelope materials, which reduced the cooling load.
    - Overall, the second case study which consisted of the methods being applied to the former one, was found to have its annual electricity use reduced to 58% of the initial conditions.
- One of the case studies analyzed by Winther & Hestness (1999) [23] was observed to have a three times lower OE than the next case study, due to a more efficient envelope and implemented energy saving systems.
- A 30% reduction was also observed by adding insulation in the analysis carried out by Fay et al. (2000) [24]. However, it was also found that despite this result, the overall life cycle improvement was significantly lower, reaching a 2.7 reduction after a period of 25 years. Moreover, the initial EE which had been required for adding the insulation in the first place requires a 12.2 years payback period.
- Several other strategies for OE reduction were collected from Keoleian et al. (2001) [25], in areas such as space and DHW heating, home appliances and lighting, space cooling, and materials used for home maintenance and improvement. The most significant reduction methods were found to be the thermal envelope improvement and more efficient HVAC system (which reduced the need for natural gas, and thus reduced the space heating consumption by 91.8%), as well as the implementation of more efficient appliances and lighting (which led to a 50% reduction of their initial consumption).
- Huberman & Pearlmutter (2005) [26] found that lightweight buildings, due to their construction, do not store heat properly and thus lead to higher OE requirements.
- Energy demand reduction was obtained by Citherlet & Defaux (2007) [27] by use of improved envelope insulation, as well as installation of a heat pump and solar collectors.
- Semi-detached dwellings were found by Cuéllar-Franca & Azapagic (2012) [28] to consume 1,000 GJ less than detached ones over their lifetime.
- In an analysis conducted by Dahlstrøma et al. (2012) [29] it was found that implementing a heat pump in a passive house reduced 40% of energy consumption, and 30% of emissions.

Table 2. Literature review summary of parameters of the buildings (part 1)

Reference	Year	Country	Buildings analyzed	Surface	Building material	Number of floors	Number of inhabitants	Building lifespan	Software/ Method used
				[m^2]				[years]	
Adalberth [21]	1997	Sweden	Dwelling 1	130	Wood	1	5	50	BEAT 2002 Enorm
			Dwelling 2	129	Wood	1	5	50	
			Dwelling 3	138	Wood	2	5	50	
Blanchard & Reppe [22]	1998	USA	Standard home (SH)	228	Wood	2	4	50	Energy-10[8] DEAM database
			Energy efficient home (EEH)	228	Wood	2	4	50	
Winther & Hestness [23]	1999	Norway	Case 1 - Norwegian IEA Task 13 experimental building	110	Wood	2	5	50	SUNCODE
			Case 2 – LEB (solar collectos + heat recovery from ventilation)	110	Wood	2	5	50	
			Case 3 – LEB (exhaust air heat pump for partial heating)	110	Wood	2	5	50	
			Case 4 – Current building practices in Norway	110	Wood	2	5	50	
			Case 5 – "Green" design in Norway	110	Wood	2	4-5	50	
Fay et al. [24]	2000	Australia	Dwelling – Green Home	128	Brick	2	4-5	100	NatHERS
Keoleian et al. [25]	2001	USA	Standard home (SH)	228	Wood	2	4	50	Energy-10
			Energy efficient home (EEH)	228	Wood	2	4	50	
Peuportier [30]	2001	France	Case 1 - Reference house	112	Concrete	1	4-5	80	EQUER, COMFIE
			Case 2 - Observ'ER house	212	Wood	1	4-5	80	
			Case 3 - CNDB house	155	Wood	1	4-5	80	
Marceau & VanGeem [31]	2002	USA	Case 1 - Wood frame	228	Wood	2	4-5	100	Visual DOE 2.6
			Case 2 - ICF	228	Concrete	2	4-5	100	
Mithraratne & Vale [32]	2004	New Zealand	Case 1 - Light construction	94	Wood	1	4-5	100	
			Case 2 - Concrete construction	94	Concrete	1	4-5	100	
			Case 3 – Super-insulated	94	Concrete	1	4-5	100	
Huberman & Pearlmutter [26]	2005	Israel	Case 1 – 1 Half-block module	112	Concrete	1	4 apartments	50	Quick II
Citherlet & Defaux [27]	2007	Switzerland	Family home V1 - Variant SIA	266	Wood	3	2	50	Lesosais, Polysun, Pvsyst
			Family home V2 - Variant Minergie	266	Wood	3	2	50	
			Family home V3 - Variant Low-energy	266	Wood	3	2	50	

Table 3. Literature review summary of parameters of the buildings (part 2)

Reference	Year	Country	Buildings analyzed	Surface [m²]	Building material	Number of floors	Number of inhabitants	Building lifespan [years]	Software/ Method used
Gerilla et al. [33]	2007	Japan	Case 1	150	Wood	-	-	35	-
			Case 2	150	Concrete	-	-	35	-
Utama & Gheewala [34]	2008	Indonesia	Case 1	50	Clay	1	4-5	40	ECOTECT
			Case 2	50	Cement	1	4-5	40	
Blengini & Di Carlo [35]	2009	Italy	Case 1 – Low energy house	367	Concrete	3	4	70	Edilclima EC501
			Case 2 – Standard house	367	Concrete	3	4	70	
Ortiz et al. [36]	2009	Spain	Case 1 – Standard house	160	Brick	2	4	50	DesignBuilder
Monteiro & Freire [37]	2011	Portugal	Case 1	132	Brick	2	4	50	Ecoinvent; Simapro 7
Cuéllar-Franca & Azapagic [28]	2012	UK	Case 1 - Detached house	130	Brick	2	3	50	-
			Case 2 - Semi-detached house	90	Brick	2	3	50	-
			Case 3 - Terraced house	60	Brick	2	3	50	-
Dahlstrøma et al. [29]	2012	Norway	Case 1 – TEK 10	187	Wood	2	-	50	SimaPro, Ecoinvent, SIMIEN
			Case 2 – Passive house	187	Wood	2	-	50	
Rossi et al. [38]	2012	Belgium, Portugal, Sweden	Case 1 – Steel house	192	Steel	2	5	-	Pleiades, Comfie
			Case 2 – Masonry house	192	Masonry	2	5	-	
Beccali et al. [39]	2013	Italy	Case 1	110	Concrete	1	3	50	TRNSYS
Iddon & Firth [16]	2013	UK	Case 1	166	Masonry	2	3	60	SAP worksheet
Rodrigues & Freire [40]	2014	Portugal	Case 1	279	Masonry	4	-	-	-
Giordano et al. [41]	2015	Italy	Case 1 – Multi-storey building	2,112	Masonry	3-6	-	-	-
			Case 2 – Detached house	184.1	Timber	2	-	-	-

Table 4. Literature review summary of OE consumption (part 1)

Reference	Buildings analyzed	CONSUMPTION OE					Life cycle energy	CO_2(-eq) emissions of OE	OE share of energy
		DHW	Heating	Cooling	Lighting	Consumers			
		[kWh/m²/y]						[kg/m²/y]	[%]
Adalberth [21]	Case 1	83.0	76.0			64.0		-	88.0
	Case 2	32.0	32.0			32.0		-	89.0
	Case 3	32.0	32.0			32.0		-	89.0
Blanchard & Reppe [22]	Case 1 - Standard home (SH)	34.11	152.3	21.9		127.9	377.0	-	93.7
	Case 2 - Energy efficient home (EEH)	20.7	14.6	6.1		60.3	138.0	-	83.4
Winther & Hestness [23]	Case 1 - Norwegian IEA Task 13 experimental building	14.5	10.0	-		38.6	86.0	-	72.0
	Case 2 – LEB (solar collectos + heat recovery from ventilation)	14.5	31.8	-		67.3	126.0	-	92.0
	Case 3 – LEB (exhaust air heat pump for partial heating)	14.5	50.0	-		67.3	142.0	-	94.0
	Case 4 – Current building practices in Norway	36.4	71.8	-		60.0	172.0	-	95.0
	Case 5 – "Green" design in Norway	36.4	54.5	-		60.0	164.0	-	92.6
Fay et al. [24]	Case 1 – Green Home	291.7					390.0	-	74.8
Keoleian et al. [25]	Case 1 - Standard home (SH)	31.7	155.9	24.4		152.3	389.9	-	91.0
	Case 2 - Energy efficient home (EEH)	23.1	12.2	6.1		60.9	155.9	-	74.0
Peuportier [30]	Case 1 - Reference house	-	-	-	-	-	-	16.1	-
	Case 2 - Observ'ER house	-	-	-	-	-	-	9.9	-
	Case 3 - CNDB house	-	-	-	-	-	-	5.2	-
Marceau & VanGeem [31]	Case 1 - Wood frame (Phoenix)	-	-	-	-	-	176.8	-	-
	Case 2 – ICF (Phoenix)	-	-	-	-	-	163.0	-	-
Mithraratne & Vale [32]	Case 1 - light construction	-	22.9	-	-	-	47.2	-	74.0
	Case 2 - concrete construction	-	20.8	-	-	-	45.1	-	71.0
	Case 3 – super-insulated	-	12.3	-	-	-	32.9	-	57.0
Huberman & Pearlmutter [26]	Case 1 – 1 Half-block module	766.4					2,289.2	15.0	33.5
Citherlet & Defaux [27]	Family home V1 - Variant SIA	5.6	62.5	-		22.2	-	20.0	-
	Family home V2 - Variant Minergie	5.6	40.8	-		25.9	-	2.5	-
	Family home V3 - Variant Low-energy	5.6	19.4	-		16.7	-	2.0	-

Table 5. Literature review summary of OE consumption (part 2)

Reference	Buildings analyzed	CONSUMPTION OE					Life cycle energy	CO_2(-eq) emissions of OE	OE share of energy
		DHW	Heating	Cooling	Lighting	Consumers			
		[kWh/m^2/y]						[kg/m^2/y]	[%]
Gerilla et al. [33]	Case 1	-	-	-	-	-	140.0	10.1	-
	Case 2	-	-	-	-	-	166.7	12.3	-
Utama & Gheewala [34]	Case 1	83.6					89.9	-	92.9
	Case 2	94.9					101.4	-	93.5
Blengini & Di Carlo [35]	Case 1 – Low energy house	22.8	10			2,188.2		5.2	
	Case 2 – Standard house		109					7.9	
Ortiz et al. [36]	Case 1 – Standard house	-	-	-	16	37	76	42.0	-
Monteiro & Freire [37]	Case 1	-	71.8	3.8	-	-	-	-	-
Cuéllar-Franca & Azapagic [28]	Case 1 - Detached house	39.0	120.5	-	11.0	13.9	188.3	63.0	-
	Case 2 - Semi-detached house	56.3	133.3	-	9.3	20.0	224.8	74.8	-
	Case 3 - Terraced house	84.5	148.3	-	8.7	30.1	280.19	92.7	-
Dahlstrøma et al. [29]	Case 1 – TEK 10	29.8	49.7	0	28.9	7.7	-	100.0	-
	Case 2 – Passive house	29.8	16.0	0	28.9	7.4	-	80.0	-
Rossi et al. [38]	Case 1 – Steel house	-	55.0	3.9	-	-	-	28.7	-
	Case 2 – Masonry house	-	57.0	3.7	-	-	-	29.3	-
Beccali et al. [39]	Case 1	22.0	26.9	7.5	-	101.6	-	-	-
Iddon & Firth [16]	Case 1	-	-	-	-	-	-	31.23	-
Rodrigues & Freire [40]	Case 1	-	-	-	-	-	-	160	-
Giordano et al. [41]	Case 1 – Multi-storey building	59.6							
	Case 2 – Detached house	61.9							

3. Case study: Townhouse Lot. 307, Green Valley

3.1. General aspects

The selected case study is part of the Belas Clube de Campo residential area, the entirety of which can be observed in Figure 4 below:

Figure 4. Overview of Belas Clube de Campo residential area (Image obtained from Belas Clube de Campo)

Located in Sintra and initiated in the 1990's, the residential neighborhood is comprised of three main stages, two of which have already been built. The third one, marked in red in Figure 4, is still a work in progress, and is so far set to incorporate 14 townhouses and an apartment building. As can be observed in Figure 5 below, only two of the townhouses have so far been completed.

Figure 5. Current status of stage 3 (Image obtained from Belas Clube de Campo)

As a result, it has been decided to select one of the two completed townhouses for the study of this thesis, more specifically the one located on Lot. 307, marked in green in Figure 6 below.

Figure 6. Location of Townhouse Lot 307 [42]

3.2. Lot 307 townhouse

The townhouse at lot 307 (Figure 7) is a semi-detached building, featuring a common wall with the next dwelling on the north side. It is built as a single-family home, with 2 floors above ground level and one below, composed of the following rooms (Table 6):

Table 6. Room distribution by floor in townhouse 307

Floor (-1)	• Parking area • Technical zone • Laundry room • Storage area • Bathroom	TOTAL SURFACE: 167.8 m^2
Floor (0)	• Hallway • Bathroom • Kitchen • Living room • Study/ Office	TOTAL SURFACE: 81.8 m^2
Floor (1)	• Master suite • Suite • 2 bedrooms • 3 bathrooms • Hallway	TOTAL SURFACE: 103.1 m^2

Figure 7. Back view and top view of Townhouse 307 (Images obtained from Belas Clube de Campo)

The rooms on each floor will be further described in **Annex 1. Townhouse 307 characteristics** according to their main features and personal observations from the study visit performed on May 29th, 2018. The design and room distribution for each floor will also be showcased by means of the FloorPlanner website [43]. More detailed figures of the modelled building can be found in **Annex 2. Townhouse modelling** (Figure 43 to Figure 50).

3.3. LiderA Certification

The 307 Townhouse has been classified as A+ according to LiderA standards. Below, Table 7 and Table 8 summarize the main findings of the energy audit performed according to the LiderA criteria [44]:

Table 7. Sustainable performance assessment of Lot 307 Townhouse (part 1) [44]

Criteria	Sub-criteria	Notable aspects
Local Integration	**Ground**	Building construction considered the land morphology. It has the required infrastructure nearby: sewage network, drinking water, electricity, telecommunications, gas connection. Townhouse includes an outdoor area with a swimming pool and seating area.
	Natural Ecosystems	The lot contains a total of 94 square meters of green area, amounting to 18% of the overall area of the townhouse.
	Landscape and Heritage	Color palette was adapted to the tones of the area. Building was properly integrated in the nearby environment.
Resources	**Energy**	Estimated annual heating energy requirements: 11 kWh/m^2year Passive design parameters were considered North part of the building is semi-detached by means of a common wall with the next townhouse. Interior space was designed in accordance to the orientation of the building, as well as the occupancy. Use of energy efficient appliances. Implementation of RES for heating, electricity and hot water production (83% share of renewables).
	Water	Use of flow reduction systems, monitoring systems etc. Rainwater storage tank, re-purposing it for non-drinking use. Surface run-off is avoided by means of vegetation, pebbles, and permeable pavement.
	Materials	Use of durable materials. Use of local materials (75-90% of national origin) Use of 75-90% low impact, recycled and renewable materials
	Food Production	Possibility of local food and aromatic herb production.
Environmental Load	**Effluents**	No wastewater treatment system. Separative sewage network, which allows for re-use of graywater.
	Atmospheric Emissions	Gas appliances are avoided to reduce emissions. Air conditioning by means of radiant flooring instead of gas heating systems.
	Waste	Waste separation by typology and danger during construction phase. Less polluting raw materials were selected. Storage area placed on the (-1) floor to allow for waste collection and separation. Recycling is encouraged.
	Outdoor Noise	Noisiest appliances are placed on the -1 floor, with acoustic insulation to avoid propagation of noise and vibrations.
	Illumination and Thermal Pollution	Adequate insulation was an important consideration. Lighting systems with an appropriate intensity were used.

Table 8. Sustainable performance assessment of Lot 307 Townhouse (part 2) [44]

Environmental Comfort	**Air quality**	Natural ventilation is used for the building., by properly arranging the townhouse placement. Attention was paid to arranging windows on opposite oriented sides of the building to allow for fast and efficient cross-ventilation. Windows such as the ones in the living room also present air intake openings in the upper parts.
	Thermal comfort	The outdoor garden serves to optimize the thermal behavior of the building. External blinds are also implemented for window shading, whereas thermal insulation maintains the interior temperatures stable. There is also a heat pump installed to provide underfloor heating.
	Lighting and acoustics	The building is designed in such a way as to take advantage of natural lighting (ex. Skylights). Shading is also used.
Socioeconomic Background	**Access for all**	The location of the townhouse is 10 min by car from the nearest train station; there is also an option for Belas transport system. Moreover, the building presents the option for EV charging.
	Economic diversity	The interior spaces of the building allow for adjustment depending on the way the inhabitants intend for them to be used. The building is a T5 typology, containing an office, 2 suites and 2 bedrooms. The PV system installed allows for local electric energy production. In terms of labour, as the land was previously unoccupied, no vacancies were created; however, the construction and operation phase of the building allow for job creation opportunities.
	Amenities and social interaction	The area contains both human amenities (cafes, restaurants, supermarkets etc.) and natural ones (as it is a rural area with green spaces). The Belas Clube de Campo contains one of the *"most prestigious golf courses in Lisbon"*, and therefore allows for an infrastructure of leisure and services. In the Green Valley part of the residential area, there are also plans for developing a health unit, an equestrian center, a school, as well as commercial and service areas.
Socioeconomic Background	**Participation and control**	The townhouse has a system installed (Bticino domotics) that allows for controlling the interior comfort conditions such as adjusting and even programming the desired output from lighting systems, AC and security systems. The same control system could allow for monitoring the energy consumption of the townhouse.
	Life cycle costs	The life cycle costs were minimized by means of using equipment belonging to good energy classes. Energy and water saving systems were also used, as well as materials which are durable for the construction of the building. Aside from the energy management system, PV panels, solar collectors and batteries provide a further method to reduce the energy bill of the townhouse.
	Innovation	The townhouse contains several innovative systems, such as the PV panels, battery, energy management system, gray water separation system and rainwater storage.
Sustainable Use	**Environmental management**	The LiderA system was used to certify that the building meets the sustainability criteria necessary. It was also ensured that the housing method would be low-density and protect the natural habitats in the area. The Belas Clube de Campo residential project was the first in Europe to audit all of the dwellings that compose it and is *"the only European residential community to comply with the European Directive on the Energy Certification of Buildings"*.

3.4. Operational energy components

3.4.1. Appliances

Regarding appliances, the main consumers were primarily identified based on the website of Green Valley [45] by looking at the townhouse interior images, then confirmed or adapted during the study visit, and even further confirmed by obtaining the list of consumers and their estimated daily consumption from Belas Clube de Campo. The complete list and their rated power, as well as estimated daily use and consumption, can be found in **Annex 3. Appliance consumption** (Table 23 and Table 24). The energy consumption was considered to be the one provided by Belas Clube de Campo for each appliance, with the assumption that the suite is reserved for guest use, and therefore no consumption was taken into account for the room and bathroom it contains.

It should be mentioned that the townhouse design seeks to promote a low impact on the environment, as all appliances installed are electrical, including the stove top and the oven. Furthermore, the garage presents the option of electrical charging for vehicles, and for this reason in the analysis of appliance consumption, the charging of one Renault Zoe (Figure 8) was also accounted for.

Figure 8. Renault Zoe model [46]

Based on data collected from the Renault website for this specific model [46], it was determined that the car requires a total charging time of 20 hours at a 2.3 kW power which is the assumed nominal power for domestic charging (marked in red in Figure 9). However, for the purpose of this analysis, a value of 3.6 kW power was used [47], and an estimated time of 8 hours for charging at home was allowed, with the rest considered to be completed at other locations (e.g. at the workplace).

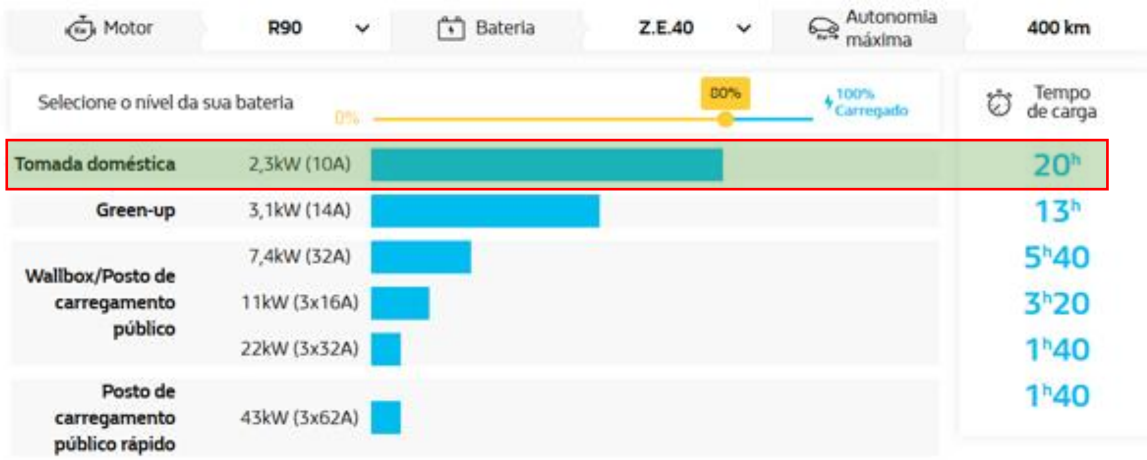


Figure 9. Charging specifications of Renault Zoe [46]

By accounting for all consumers, as well as assuming a 10% yearly period allocated for holiday time [48], the appliance-related energy consumption was determined to be 20,243 kWh/year.

3.4.2. Lighting

Based on personal observations during the study visit, as well as the LiderA report of the townhouse [44], the following conclusions can be drawn regarding the lighting system of the selected location:

- Lighting is mostly done by means of LED lamps and lightbulbs.
- Occasionally, use of non-LED lamps was observed in several locations around the house.
- Use of natural lighting is encouraged by means of large windows, especially on the western side of the building where the master suite, room 1, and one balcony are located. Moreover, the palette of colors used for walls is very light, which allows for light to reflect and fill the rooms even more. Skylights are also installed in the upper bathrooms to further profit from natural light.

A complete list of lighting systems by room, as well as their rated power, assumed use per day and daily energy consumption can be found in **Annex 4. Lighting consumption** (Table 25 and Table 26). Lighting use per day was adapted by looking into appliance use as well, and no lighting was assumed to be required for the guest suite. The abbreviations used for the rooms are explained in Table 9 below:

Table 9. Room abbreviations used

Room	Room code		Room	Room code
Parking area	P		Bathroom (MS)	B3
Technical zone	TZ		Suite	SU
Laundry room	LR		Bathroom (SU)	B4
Storage	S		Room 1	R1
Bathroom (-1)	B1		Room 2	R2
Hall (0)	H		Bathroom (R1 and R2)	B5
Kitchen	K		Terrace	T
Living Room	L		Pool	P2
Study	ST			
Bathroom (0)	B2			
Hallway (1)	H2			
Master Suite	MS			

As the exact type of lightbulbs used could be determined only for the LEDs used in lamps, the following assumptions were made regarding the lightbulbs used in other areas of the townhouse (Table 10):

Table 10. Lighting assumptions

Lighting system	Type	Model used	Rated power	Reference
Suspended lighting	LED	Climar SPY Recessed 55 LED	0.05 kW	[49]
Square ceiling light	LED	HiB Inertia LED	0.02 kW	[50]
Recessed spotlight	LED	PCE-DL7W	0.01 kW	[51]
Ceiling lighting	LED	SPY Trimless 33 LED	0.05 kW	[52]
Surface profile lighting	LED	SPY Surface 55 LED	0.03 kW	[53]

The total consumption of lighting for townhouse 307 was determined to be 852.9 kWh/ year. The same 10% adjustment was conducted in order to allow for holidays, and the end value became 767.6 kWh/year.

3.4.3. Heating and cooling

As mentioned before in **1.3.2 Methodology,** heating and cooling of the townhouse present certain specific aspects.

Heating of the building is done by means of floor heating and an installed heat pump which is further described in **Section 3.4.6 Renewables**. According to the energy certificate of the building, due to the high efficiency of the pump, it is assumed that the heating needs, totaling 11 kWh/m^2/year useful energy, are completely covered from renewable sources (Figure 11). Efforts were also made to reduce the requirement of energy itself through the implemented design, by not only installing no windows on the northern side, but also using that specific façade as a connecting one with the townhouse in the next lot [44]. External roller blinds are also used for the rooms on the upper floor to further insulate them when necessary.

Figure 10. View of closed (left) and open external roller blinds

Regarding cooling, due to good insulation as well as proximity to a forest area, no energy is considered to be required (Figure 11).

Figure 11. Heating and cooling energy requirements and share of energy from renewable sources

3.4.4. Ventilation

At present, no system is installed for managing the ventilation of all rooms with the exception of the bathrooms. As mentioned previously in the LiderA criteria, the townhouse design focuses mostly on natural ventilation by means of vents installed, where possible, on room facades which face opposite directions, so as to encourage natural and rapid ventilation of said rooms. Moreover, several window frames present air intake openings, which have self-regulating grids (Figure 12).

Figure 12. Example of air intake openings on living-room window

3.4.5. Domestic Hot Water (DHW)

The townhouse consists of a total of 5 bathrooms, located as follows: one on the basement floor, one on the ground floor, and three on the first floor (one for each suite and one shared between the remaining two simple bedrooms). They are each equipped with a shower, with the exception of one, which contains a bathtub. Two of them are also equipped with bidets.

It was found that the average DHW consumption per person per day in residential buildings amounts to 50 liters per day [54]. Considering the efficiency of the building under analysis, a value of 40 l/person/day will be assumed, for each of the supposed 4 occupants. This brings the daily DHW requirement to 160 liters per day, and 58,400 liters per year. When integrating the 10% vacation time initially considered, the total requirement for domestic hot water becomes 52,560 liters per year.

Further, the washing machine and dishwasher consumption will be considered, by looking at the model of the appliances used and using the nominal number of yearly cycles of use described in their specifications. As a result, for the Siemens IQ500 - SN66M039EU dishwasher [55], a total of 280 cycles of 9.5 liters each will be assumed, totaling 2,660 liters per year. For the Siemens IQ500 - WM10T408ES washing machine [56], 220 cycles of 44 liters each will be considered, totaling 9,680 liters per year. It should also be mentioned that both appliances are class A++ and A+++ respectively, thus more efficient in terms of energy consumption.

The total values obtained showed a requirement of 64,900 liters of hot water per year. This value was then converted into yearly energy requirement by means of formula (1) below [57]:

$$\mathrm{Q} = \mathrm{m} * \mathrm{Cp} * \Delta\mathrm{t} \quad (1)$$

Where

Q = Heat required

m = Mass of heated water

Cp = Heat capacity of water (4.186 J/kgK)

Δt = Temperature difference

By replacing the mass of heated water with a parameter involving the already known volume of water to be heated from formula (2), as well as defining the two temperatures that give the previous Δt, equation (1) becomes the more developed one in (3):

$$\rho = \frac{m}{V} \quad (2)$$

Where

ρ = Density of water (1,000 kg/m^3)

V = Volume of water

$$Q = V * \rho * Cp * (t_h - t_c) \quad (3)$$

Where

t_h = Temperature of hot water (60 °C)

t_c = Temperature of cold water (15 °C)

Based on this last formula, it can be determined that the total energy required for DHW is 3,395 kWh per year.

According to the LiderA energy certificate of the building, a large share of the DHW is covered by the 2 flat-plate solar collectors installed. The rest, confirmed by Nuno Remédios, Civil Engineer at Belas Clube de Campo, is obtained by means of electric resistance, as the townhouse contains a water tank which can electrically heat the water when there is no sunshine.

3.4.6. Renewables

PV PANELS

The consumption of lighting and appliances is assumed to be covered in part at least by the solar PV panels installed on the rooftop. The system, consisting of 13 GENIUS 4BB 250 W free-standing panels, is installed on the rooftop of the townhouse, facing South at an angle of 35 degrees. Panel specifications can be found in **Annex 5. PV panel specifications.**

SOLAR COLLECTORS

2 Vulcano FKC-2W flat-plate solar collectors are also installed on the roof of the building, facing South at the same inclination as the PV panels. The same placement is mirrored on the townhouse with which a common wall is shared (Figure 13). Complete specifications for the solar collectors can be found in **Annex 6. Solar collector specifications**.

Figure 13. View of Townhouses 307 and 306 rooftops (Image obtained from Belas Clube de Campo)

HEAT PUMP

A heat pump is also installed on the basement floor, as marked previously in Figure 25 on the South side of the building. The system is a Daikin (ERLQ016CAV3/ EHSXB16P50BA) outdoor/indoor system (Figure 14), with a power of 15.34 kW and COP of 4.10 [58]. This is used for underfloor heating in the two floors that contain living spaces, namely (0) and (1), over a total useful surface of 184.9 m^2.

Figure 14. Daikin heat pump installed

4. Analysis

4.1. Current status – emissions without RES

The energy for heating and cooling will not be considered for further calculations, as the heating load is covered by the heat pump and cooling is not considered to be required, due to good insulation as well as proximity to a forest area. As ventilation is done mostly by natural means and through very efficient vents installed in bathrooms, it will also not be considered. In the end, the analysis conducted in this thesis will focus on the three main consumers summarized below in Table 11:

Table 11. Lighting, appliances and DHW consumption

Parameter	Consumption	Unit
Lighting	767.6	[kWh/year]
Appliances	20,243	[kWh/year]
DHW	3,395	[kWh/year]

By assuming an initial case of no renewable energy systems installed in the townhouse, the base environmental impact can be determined. For this, it will be considered that lighting and appliances take their required energy directly from the grid, and the CO_2 emissions are therefore directly dependent on the energy mix of Portugal. Based on this, a reference value for CO_2 emissions can be determined [59].

The total primary energy supply for Portugal was obtained for 2018 from APREN (Associação Portuguesa de Energias Renováveis) [60] and is represented in the graph below (Figure 15).

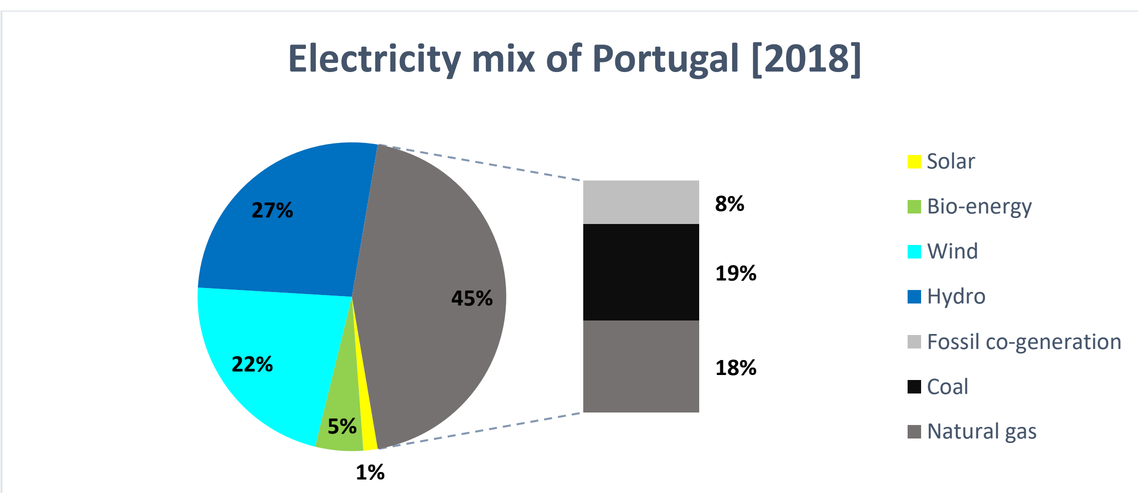


Figure 15. Electricity mix of Portugal (2018) - Adapted from [60]

If the share of fossil fuels in Figure 15 is then applied to the energy requirements for lighting , DHW and appliances, then the energy covered by each fossil fuel type can be determined (Table 12).

Table 12. Energy requirements for coal, oil and natural gas for no RES scenario

		Lighting	**Appliances**	**DHW**
Actual consumption	[kWh/year]	767.6	20,243	3,395
Gas consumption (17.72% share)	[kWh/year]	136	3,587	602
Coal consumption (18.62% share)	[kWh/year]	143	3,769	632
Co-generation consumption (8.31% share)	[kWh/year]	64	1,682	282

By using the specific CO_2 emissions presented in Table 13 below, the emissions related to lighting and appliance energy use become:

- 93.1 kg CO_2 emissions per year for lighting;
- 2,453 kg CO_2 emissions per year for appliance use;
- 411.4kg CO_2 emissions per year for DHW use (it is assumed that the DHW requirement is covered by means of an electrical boiler).

Table 13. Specific Carbon Dioxide Emissions of Various Fuels [61]

Fuel	**CO_2 emissions**	**Unit**
Natural gas	0.20	[kg CO_2/kWh]
Coal	0.34	[kg CO_2/kWh]
Fossil co-generation*	0.27	[kg CO_2/kWh]

*for co-generation, a 50% to 50% proportion of gas and coal will be assumed

Overall, a total baseline of 2,958 kg of CO_2 emissions per year is obtained.

4.2. Current status – emissions with RES production

4.2.1. Solar PV electricity generation

The following steps were used in the calculation of solar PV generation (Figure 43):

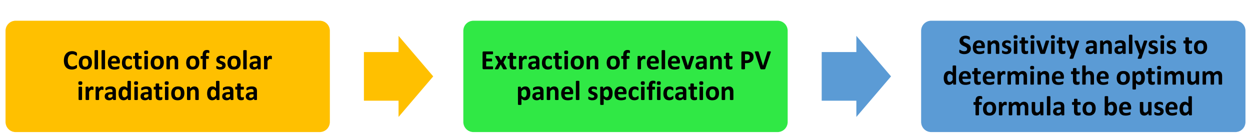


Figure 16. Steps for solar PV determination

The first step consisted of collecting the solar irradiation data for the location selected, for an inclination of 0 degrees due to the flat placement of the PV panels on the rooftop (Figure 17).

Figure 17. PV panel horizontal placement on rooftop

Due to the proximity of the location to the Portuguese capital, the city of Lisbon was selected for irradiation data collection due to the higher probability of obtaining data. The mean monthly values were collected from the European Commission Joint Research Centre (JRC) [62] and are compressed into Table 14 below. The table also includes the sunlight hours.

Table 14. Mean monthly irradiation data [62]

Month	Solar irradiation G [Wh/m^2/day]	Sunlight hours [h]
January	2,180.0	3.5
February	3,210.0	7
March	4,680.0	7
April	5,640.0	8
May	6,680.0	9
June	7,450.0	10
July	7,620.0	11
August	6,880.0	10
September	5,400.0	8
October	3,800.0	6
November	2,510.0	5
December	1,950.0	4

From all the specifications of the PV panels, only several key parameters were necessary for the calculations and are included in the table below (Table 15):

Table 15. PV panel data for the calculations

PV data	Nominal power	P_N	[W]	250.0
	PV panel area	A_P	[m²]	1.6
	Array area	$A = n^* A_P$	[m²]	21.2
	Performance Ratio	PR	[%]	0.8
	Efficiency	r	[%]	0.2
	Number of PV panels	n	[-]	13.0
	Array power	$P = n^* P_N$	[kW]	3.3

In the initial search for the appropriate formulas to use in calculations, several variants were observed. For this reason, an initial sensitivity analysis was conducted for the obtained formulas, and three variants were found to yield similar results. Therefore, that common value was assumed as the energy produced by the PV panels.

METHOD 1

A primary method [63] used the following formula (4) for calculating the energy produced by a PV system:

$$E = A * r * G * PR \tag{4}$$

Where

E = Energy produced [kWh];

A = Array total surface [m^2];

r = Solar panel efficiency [%];

G = Solar irradiation [kWh/m^2/day];

PR = Performance coefficient (assumed as default value, 0.75).

This method used an average yearly value for the solar irradiation (in this case 4,833.3 Wh/m^2/day) and generated a total of 4,309 kWh per year. The website also provided an Excel sheet for more rapid calculations, which confirmed the value obtained in the thesis model.

METHOD 2

A second method [64] used a similar formula (5):

$$E = G * PR * P * \text{no of days} \tag{5}$$

Where

E = Energy produced [kWh];

G = Solar irradiation [kWh/m^2/day];

PR = Performance coefficient (assumed as default value, 0.75);

P = Array power [kW].

This method also used the average solar irradiation value, and obtained a similar yearly production of 4,300 kWh/year.

METHOD 3

A third method made use of the same European Commission Joint Research Centre (JRC) [62] website, which also allows for marking the chosen location of implementation for a PV system, as well as mounting options, panel types and installed surface. The website then generated a total energy production of 4,270 kWh/year.

Due to the similarities in results of the three methods, a final value of 4,300 kWh/year was assumed as the PV panel energy yield. As the energy certificate of the townhouse and the LiderA report [44] did not report any values for energy production, there was no ground for comparison of the obtained value. (**Note:** The values were later confirmed with Professor Filipe Méndes)

This value accounts for almost 18% of the energy requirements for appliances and lighting discussed in previous chapters.

4.2.2. Solar collector generation

For the solar collector energy production, the following parameters of the collectors were required in the calculations (Table 16):

Table 16. Collector parameters required for calculations

Collector data	Collector area	A_C	[m^2]	2.37
	Collector absorber area	A_A	[m^2]	2.18
	Rated flow		[l/h]	50
	Optical efficiency	η_0	[%]	0.77
	1st order heat loss coefficient	a_1	[W/m^{2}K]	3.871
	2nd order heat loss coefficient	a_2	[W/m^{2}K]	0.012
	Number of collectors	n	[-]	2
	Total useful surface	A	[m^2]	4.36

A scoping study conducted in 2015 at the University of Strathclyde in the UK produced the calculation method [65] used for determining the solar thermal energy production for the case study analyzed. In this study, the following formula (6) was used to define the solar input of solar thermal collectors:

$$Q_s = A_{ap} * \eta_0 * S * Z_{panel} * UF * f_1 * f_2 \quad (6)$$

Where

- Q_s = Solar input [kWh/year]
- A_{ap} = Aperture area of collector [m^2]
- η_0 = Zero loss collector efficiency
- S = Total solar radiation on collector [$kWh/m^2/year$]
- Z_{panel} = Overshading factor for the solar panel
- UF = Utilization factor
- f1 = Collector performance factor
- f2 = Solar storage volume factor

The parameters were then determined separately, according to the study guidelines [65].

Aperture area of collector [A_{ap}]

According to the solar collector specifications [66], A_{ap} = 2.25 m^2 * 2 collectors = 4.5 m^2.

Zero loss collector efficiency [η_0]

Also based on the specifications of the collector [66], η_0 = 0.77.

Total solar radiation on collector [S]

$$S = 0.024 * \sum_{n=1}^{12} n_m * S(orient, p, m) \quad (7)$$

Where

- N_m = number of days in the respective month
- $S_{(orient,p,m)}$ = Total solar radiation incident upon the collector, corrected for orientation and tilt for each month

$$S(orient, p, m) = S_{h.m} * R_{h-inc}(orient, p, m) \quad (8)$$

Where

- $S_{h,m}$ = horizontal solar flux [W/m^2]

- $R_{h\text{-}inc(orient,p,m)}$ = Correction factor to convert horizontal solar flux to vertical or inclined for a given orientation and tilt.

$$R_{h-inc}(\mathrm{orient}, p, m) = A * \cos^2(\Phi - \delta) + B * \cos(\Phi - \delta) + C \qquad (9)$$

Where

- $A = k_1 * \sin^3\left(\frac{p}{2}\right) + k_2 * \sin^2\left(\frac{p}{2}\right) + k_3 * \sin(\frac{p}{2})$
- $B = k_4 * \sin^3\left(\frac{p}{2}\right) + k_5 * \sin^2\left(\frac{p}{2}\right) + k_6 * \sin(\frac{p}{2})$
- $C = k_7 * \sin^3\left(\frac{p}{2}\right) + k_8 * \sin^2\left(\frac{p}{2}\right) + k_9 * \sin\left(\frac{p}{2}\right) + 1$
- Φ = Latitude = 38.72 degrees
- δ = Solar declination per month, which was taken from the study (Table 17)

Table 17. Solar declination values [65]

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
δ	-20.7	-12.8	-1.8	9.8	18.8	23.1	21.2	13.7	2.9	-8.7	-18.4	-23.0

The angle "p" refers to the tilt of the solar panels. By knowing that the panels are placed almost horizontally on the flat rooftop, an angle of 0 degrees is assumed for the tilt. Therefore A and B become 0, and $R_{h\text{-}inc(orient,p,m)}$ becomes equal to C, which is 1; it can then be assumed that $S_{(orient,p,m)}$ is equal to $S_{h,m}$. For this analysis, an alternate method was used to determine the value to be used for S, due to the availability of data for the parameter in Lisbon conditions:

- According to the map present on the Global World Atlas Website [67], the solar irradiation for the chosen location falls between 1,700 – 1,800 kWh/m^2/year.
- Based on SolarGis maps [68] for the same location, the value is around 1,750 kWh/m^2/year.
- By using the estimated average value of 4.43 kWh/m^2/day [69], the yearly value becomes 1,617 kWh/m^2/year.

Considering the different values determined, an average of 1,725 kWh/m^2/year will be used for the S parameter in further calculations.

Overshading factor [Z_{panel}]

According to Table 18 taken from the study used [65], the overshading factor was determined to be 1, as the solar collectors are placed on the flat rooftop, with no obstructions present.

Table 18. Overshading factor values [65]

Z_{panel}	Overshading	% of sky blocked
0.50	Heavy	> 80%
0.65	Significant	60% - 80%
0.80	Modest	20% - 60%
1.00	None/very little	< 20%

Utilization factor [UF]

$$UF = 1 - e^{\left(-\frac{1}{H8}\right)} \quad (10)$$

Where

- H8 = Ratio of the annual solar energy available to the annual heating load = 1.79

$$H8 = \frac{S_{available}}{Annual\ heating\ load} = \frac{A_{ap} * \eta_0 * S * Z_{panel}}{Annual\ heating\ load} = \frac{4.5*0.77*1{,}750*1}{3{,}395} = 1.79 \quad (11)$$

- Annual heating load = 64,900 l/year = 3,395 kWh

$$Q = m * Cp * \Delta t = V * \rho * Cp * (t_h - t_c) = 64.9\ m3 * \frac{1000kg}{m3} * 4186 \frac{J}{kgK} * (60 - 15)K \quad (12)$$

UF = 1 – 0.57 = 0.43

Collector performance factor (f_1)

$$a^* = 0.892 * (a_1 + 45 * a_2) = 3.93 \quad (13)$$

Where

- a_1 = collector first order heat loss coefficient = 3.871 [66]
- a_2 = collector second order heat loss coefficient = 0.012 [66]

$$\frac{a^*}{\eta_0} = 5.11 < 20 \quad (14)$$

As a result:

$$f_1 = 0.97 - 0.0367 * \left(\frac{a^*}{\eta_0}\right) + 0.0006 * \left(\frac{a^*}{\eta_0}\right) = 0.79 \quad (15)$$

Collector performance factor (f_2)

$$f_2 = 1 + 0.02 * \ln\left(\frac{V_{eff}}{V_a}\right) = 1.1 \tag{16}$$

Where

- V_{eff} = effective solar storage volume [l] = 300 l
- V_d = average daily hot water demand [l] = 65,600/365 l = 179.7 l

$$V_{eff} = V_s + 0.3 * (V_c - V_s) \tag{17}$$

V_{eff} will be assumed as 300 liters.

In the end, the solar input of solar thermal collectors becomes:

$$\begin{aligned} Q_s = {} & A_{ap} * \eta_0 * S * Z_{panel} * UF * f_1 * f_2 \\ & = 4.5\, m^2 * 0.77 * \frac{1{,}750\ \frac{kWh}{m^2}}{year} * 1 * 0.43 * 0.79 * 1.1 \\ & = 2{,}284\ \frac{kWh}{year} \end{aligned} \tag{18}$$

4.2.3. CO_2 emissions

By considering 19% of energy reduced for lighting and appliances, as well as 67% reduction in DHW energy requirements, the CO_2 emissions can be re-calculated. This is done by using the same energy mix as in the previous sub-chapter and considering the rest of the DHW requirements to be covered by an electrical installation. The estimated consumption for a heater to cover the remaining DHW demand becomes 1,116 kWh per year [70].

The environmental impact therefore becomes the one featured in Table 19.

Table 19. Current status of environmental impact, considering implemented RES

		Lighting + Appliances
Initial consumption	[kWh/year]	21,011
Share not covered by RES	[%]	81
	[kWh/year]	17,019
Water heater requirement	[kWh/year]	1,112
CO_2 emissions	[kg CO_2/year]	2,160

In total, the new CO_2 emissions sum up 2,160 kg/year, representing a 27 % reduction of the initial 2,958 kg.

4.3. Scenarios for potential improvement

4.3.1. Scenario selection

By analyzing the obtained shares of renewable energy production for each of the operational energy categories, various scenarios will be analyzed for even further energy consumption reduction where necessary. Possible improvements include:

- Installation of more efficient lighting systems (such as LED's);
- Installation of lighting sensors in all rooms of the building;
- Use of natural lighting as much as possible;
- Use of energy efficient appliances;
- Efficient time management of appliance use;
- Use of reduced flow sanitary installations;
- Rainwater collection for reduced water consumption from the grid;
- Additional installation of solar collectors for DHW production;
- Additional installation of photovoltaic panels for electricity production, and more.

From these, the specific improvements already considered by the building and described in Sub-chapter **3.3 LiderA Certification** and in **Annex 1. Townhouse 307 characteristics** will be discarded, and the focus will be directed to the energy reduction methods not currently in use. For each of the scenarios, the new energy requirements will be considered, and the same steps will be followed as for the current scenario, with the added analysis of investment required versus benefits obtained.

A comparison of the proposed measures' benefits and costs will be generated, and the optimal measures highlighted for possible further improvements of the location chosen.

The potential scenarios for OE reduction will be further analyzed in Chapter 4.3.2 below; improvements will be classified according to the field to which they relate. The main categories analyzed can be found below in Figure 18, and each of them will contain several potential improvements, which will then be analyzed to observe their viability and whether the methods are already in use. In the end, the methods selected for further analysis will be described and justified.

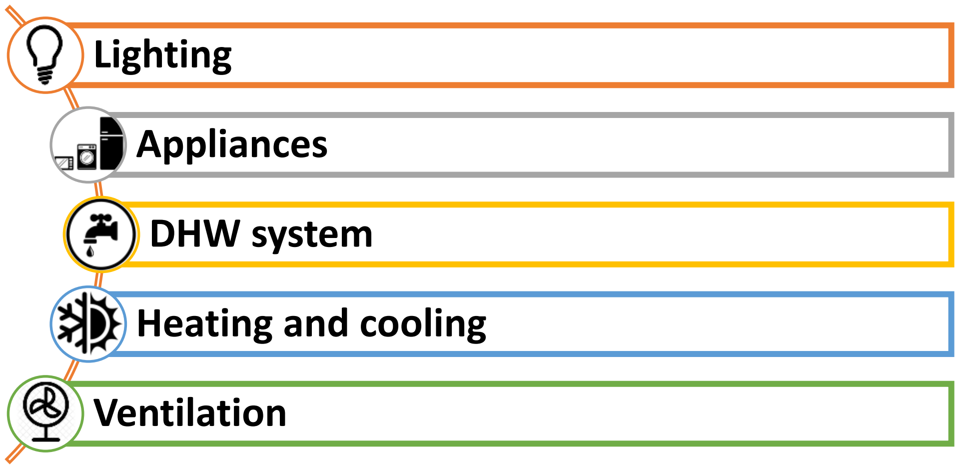


Figure 18. Categories used for improvement assessment

The potential methods for each category were further analyzed below in Table 24 and Table 25.

Table 20. Methods proposed for OE reduction and assessment of their viability for further analysis (part 1)

CATEGORY	METHOD	ANALYSIS
	1. Implementation of lighting sensors to reduce lighting consumption	Parts of the building such as the stairs and garage are already fitted with sensors
	2. Use of all LED lightbulbs	Most of the lighting fixtures in the townhouse have already been assessed as LED (see **Annex 4. Lighting consumption**)
	3. Use of natural lighting	As discussed in Chapter 3.4.2, natural lighting is already being used through large windows facing east and west, as well as skylights implemented in bathrooms above the showers.
	4. Use of energy efficient appliances	The appliances used in the townhouse are already highly energy efficient (for instance the washing machine is a Class A+++ energy efficient appliance).
	5. Use of electrical appliances to reduce environmental impact	All appliances installed in the townhouse are electrical.
	6. Efficient time management of appliances	While it is undoubtedly a method by which energy consumption can be reduced even further, it is difficult to assess the precise amount of savings. However, as the townhouse presents an installed domotics system which allows for easy management of the systems installed, as well as for an overview of the consumption, it is possible to shut down all systems in the building whenever leaving or when it is required, which contributes for savings as well.
	7. Additional PV panel installation to increase RES share	As the system now comprises of 13 PV panels and covers 18% of the electrical energy demand, added panels could have an even higher impact. However, care should be taken when considering the remaining available surface on the roof of the building.

Table 21. Methods proposed for OE reduction and assessment of their viability for further analysis (part 2)

CATEGORY	METHOD	ANALYSIS
	8. Use of sanitary systems with reduced water flow	The building already uses equipment with flow reduction, as well as water counters and monitoring systems [44].
	9. Additional collectors installed to increase RES share	Currently, the townhouse contains 2 solar collectors installed on the rooftop, which cover 72% of the DHW demand. While the addition of one more collector could help cover an even higher share, anything more would be redundant as the system would require an electrical back-up anyway for night-time use.
	10. Improved building envelope	While it has been observed in the literature review (Chapter 2.5) that improving the envelope of a building can yield significant results, it has also proven on occasion to require an EE that is quite significant and would take over 10 years to obtain a payback. Moreover, as the building is newly constructed and will be released for use soon, making further envelope adjustments may prove problematic, especially as the heating requirement is already assumed to be covered by the heat pump.
	11. Heat pump installation	A heat pump is already installed and set to cover the entire heating demand.
	12. Use of natural ventilation	Natural ventilation is already considered, by using vents on opposing facades of the same room as much as possible to allow for even more efficient ventilation.
	13. Use of ventilation in bathrooms	This method is proposed more for maintaining a recommended level of humidity than for energy reduction. It is already installed in all bathrooms of the townhouse.

In the end, the following methods have been chosen for further assessment:

1) Replacement of all non-LED lightbulbs with LED ones;
2) Replacement of the currently existing hot water tank with one of higher capacity;
3) Addition of more PV panels depending on the available rooftop surface.

4.3.2. Analysis

<u>LIGHTING</u>

Based on **Annex 4. Lighting consumption**, it can be seen that at present lighting is consuming around 768 kWh/year. Also, from the total of 69 lightbulbs and fixtures installed, only 7 of them were found to be non-LED, but rather round filament lightbulbs of 40W. By converting them to LED systems with an equivalent functionality [71], it was decided to replace them with 8W LED lightbulbs.

In this way, the lighting requirement became 431 kWh/year, leading to a 44% reduction in lighting consumption. Assuming a cost of 4.9 €/unit [72], the investment required for this improvement is 34.3€.

<u>SOLAR COLLECTOR</u>

By adding one other solar collector to the other 2 already installed, the Excel model shows the system as covering the DHW demand completely. However, it is necessary to assume at least a margin for water used at night-time which cannot be covered completely by solar collectors. For this reason, no added collector will be considered. Instead, for the purpose of the analysis, the hot water storage tank will be assumed to be replaced with a 500-liter one instead of the current, 300-liter tank. Savings of 211 kWh/year are observed, even less than the ones obtained from lighting improvements. Should the tank size be increased, these savings would rise as well; however, it would be redundant to do so due to the size of the building and the number of occupants, who only consume a maximum of 180 liters per day according to the assumptions previously made. An investment of 1,800 € would be required by this scenario.

<u>PV PANELS</u>

Before the analysis, the current aspect of the rooftop (Figure 19 and Figure 20) was analyzed in order to determine the viable number of additional panels to be installed.

Figure 19. Overview of townhouse rooftop and RES installed (Image obtained from Belas Clube de Campo)

Figure 20. Spacing of collectors and PVs on rooftop (closer view)

From the figures above, it can be observed that while the rooftop allows for quite a bit of available space, especially due to the low inclination at which the panels are installed, care should be taken to allow space for movement as well, for maintenance purposes. Therefore, in the analysis, a total of nine PV panels is considered, with the installation locations marked in Figure 21 below.

Figure 21. Proposed installation of collector and PV panels

For the proposed layout, the initial 4,300 kWh/year generation from PV panels becomes 7,277 kWh/year, which is an almost 70% increase of energy generation. The system also covers 14% more of the energy requirements for lighting and appliances, for an estimated investment of 2,250 €. As the actual product cost could not be obtained, an estimation was done based on the various 250W polycrystalline panels available on the market.

5. Results and discussion

By considering the three proposed scenarios and their combinations, the final possible proposals and their characteristic results can be found in Table 22 below. Savings are considered compared to the current status of the townhouse, and for a lifetime of 50 years. Complete results of all scenarios can be found in **Annex 7. Final scenario results** (Table 31).

Table 22. Summary of results for all scenarios considered

Scenario no.	Scenario	New DHW heater consumption	Energy savings	Emissions savings	Investment required	Cost savings
		[kWh/year]	[kWh/year]	[kg CO_2/year]	[€]	[€/50-year lifetime]
1	LED	1,112	336	41	34	3,836
2	Collector	901	211	26	1,800	2,407
3	PV	1,112	2,977	361	2,250	33,994
4	LED + Collector	901	547	66	1,834	6,249
5	LED + PV	1,112	3,313	402	2,284	37,836
6	LED + Collector + PV	901	3,524	439	4,084	40,248

<u>ENERGY SAVINGS</u>

As can be observed in the graph below (Figure 22), combining the scenario of lighting and collectors gives significantly less savings than simply the scenario involving PV panel increase. However, combining all three proposed methods can reach a total savings value of 3,524 kWh/year (14% of the current yearly energy demand), and even 176,218 kWh for the assumed lifetime of 50 years.

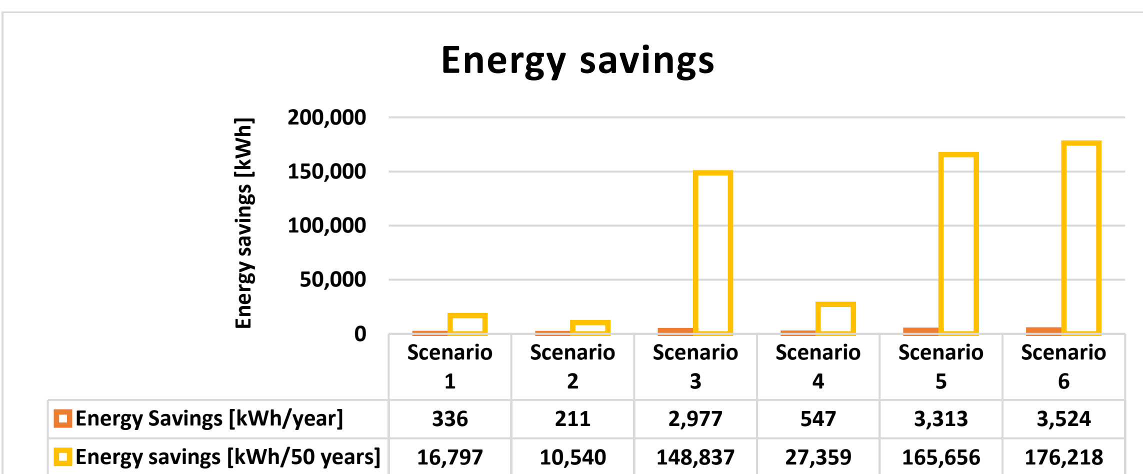
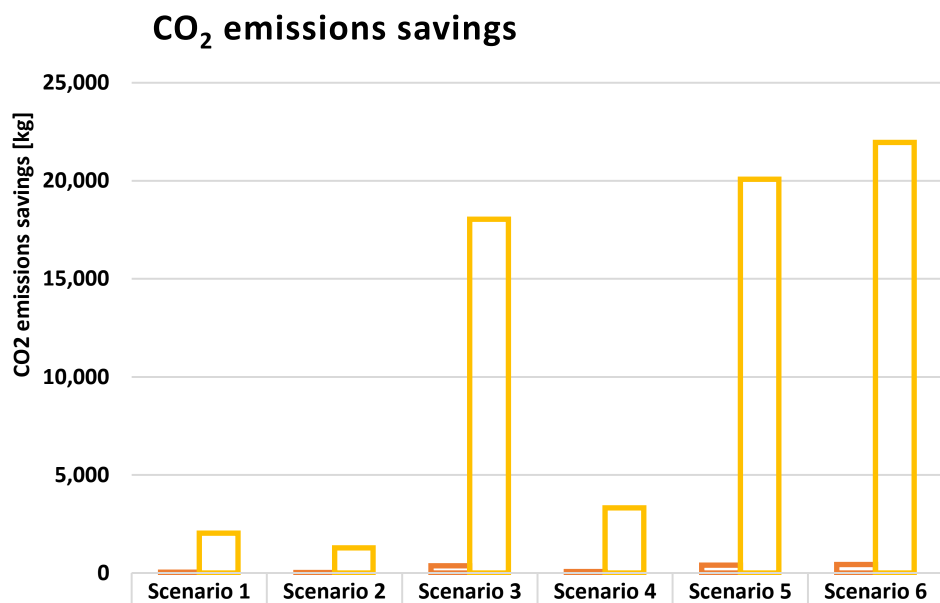


Figure 22. Yearly and lifetime energy savings for all scenarios

<u>OPERATIONAL CARBON SAVINGS</u>

As the townhouse is already highly efficient, CO_2 emission savings are understandably low, as represented in Figure 23. When combining all three scenarios, a maximum saving of around 439 kg per year is observed, and 22 tons for the entire lifetime considered.

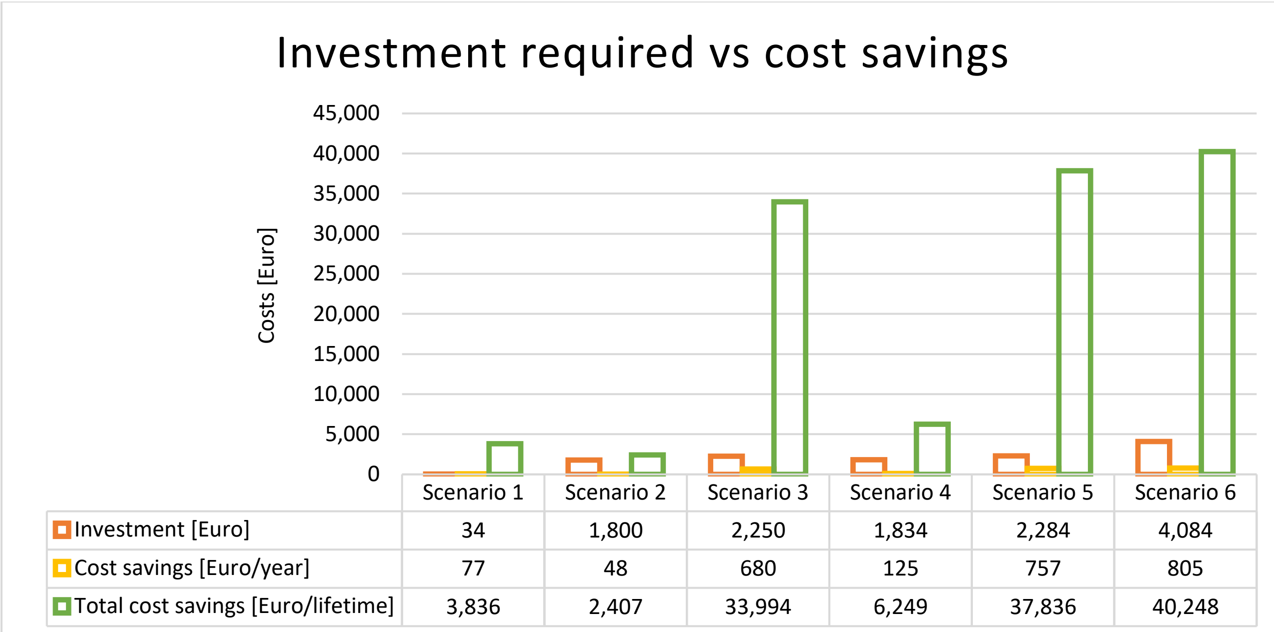


	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5	Scenario 6
Emissions savings [kg CO2/year]	41	26	361	66	402	439
Emissions savings [kg CO2/lifetime]	2,035	1,277	18,037	3,315	20,075	21,949

Figure 23. Yearly and lifetime emissions savings for all scenarios

COST SAVINGS

By using the energy cost for households in Portugal as 0.2284 €/kWh [73], cost savings of up to 805 €/year can be observed for the combined improvements scenario. When comparing these savings with the initial investments required (see Figure 24), the conclusion can be drawn that the payback will take place in a little over 5 years, thus making the proposed scenario a viable one.



	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5	Scenario 6
Investment [Euro]	34	1,800	2,250	1,834	2,284	4,084
Cost savings [Euro/year]	77	48	680	125	757	805
Total cost savings [Euro/lifetime]	3,836	2,407	33,994	6,249	37,836	40,248

Figure 24. Yearly and lifetime cost savings versus investment for all scenarios

As can be observed from the results discussed above, for an already highly energy-efficient building, while there is no high potential for operational carbon savings, there is a definite possibility for further energy savings, and implicitly for cost savings.

Based on these observations, it can be concluded that the methodology applied proved viable, and it also confirmed the initial hypothesis of the thesis, which stated that operational energy had the potential to be lowered for the building considered. The improvements can be reduced even further by installing even more photovoltaic systems where space can be found, in order to reduce the still-high electricity consumption.

Aside from the three base scenarios considered, there is also the potential for further reduction of OE from the human component. This refers to the possibility of energy savings by encouraging the people who will take residence in the townhouse to use energy responsibly.

Note: It should be mentioned that the PV and collectors' costs are subject to variations, as only their initial cost was considered in the analysis, without the installation cost.

While the analysis has proven that the method considered has potential for energy savings, the final ideal scenario can be easily adapted for all types of dwellings, with the possibility of even more significant reductions of OE costs than in the energy-efficient case study considered.

6. Conclusion & future work

The present thesis described a method for reducing the operational energy of a class A+ energy efficient building according to the LiderA certification system. For this purpose, an initial “energy audit” was performed by means of a study visit and data collection. A literature review was conducted in parallel in order to observe energy requirements for various parameters of the OE, as well as solutions proposed by different author for reducing OE costs and CO_2 emissions. Then, the selected location was analyzed in terms of consumption and operational carbon first for no renewable energy systems installed, then for the current scenario for observations.

Based on the energy savings measures collected from the literature review, as well as others which were already known to reduce OE, 3 base scenarios were developed, namely lighting replacement with all LED lightbulbs, additional solar collector installation and additional PV installation. Their various combinations were also analyzed, and the final combined scenario was deemed to be ideal, as it provided savings of almost 3,524 kWh/year (representing 14% of the current energy consumption) and required a payback period of around 5 years.

This analysis proved that OE reduction is possible even for an already efficient house, which shows that even in a best-case scenario, improvements can already be made. Moreover, since the method proposed proved viable in this situation, it can then be applied to less efficient buildings as well and potentially have an even higher impact on their savings.

For future works, several options might be intriguing to look into:

- A more detailed cost analysis can be conducted to determine the exact investment and cost savings for the considered scenarios;
- A scenario may be considered where the 250W PV panels are replaced with more efficient ones instead;
- As the building is currently un-inhabited, it would be interesting to observe the load profile of the consumption after a year of habitation. Measures can then be proposed to implement peak shaving and obtain a more constant consumption curve.

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Annex 1. Townhouse 307 characteristics

Floor (-1) description

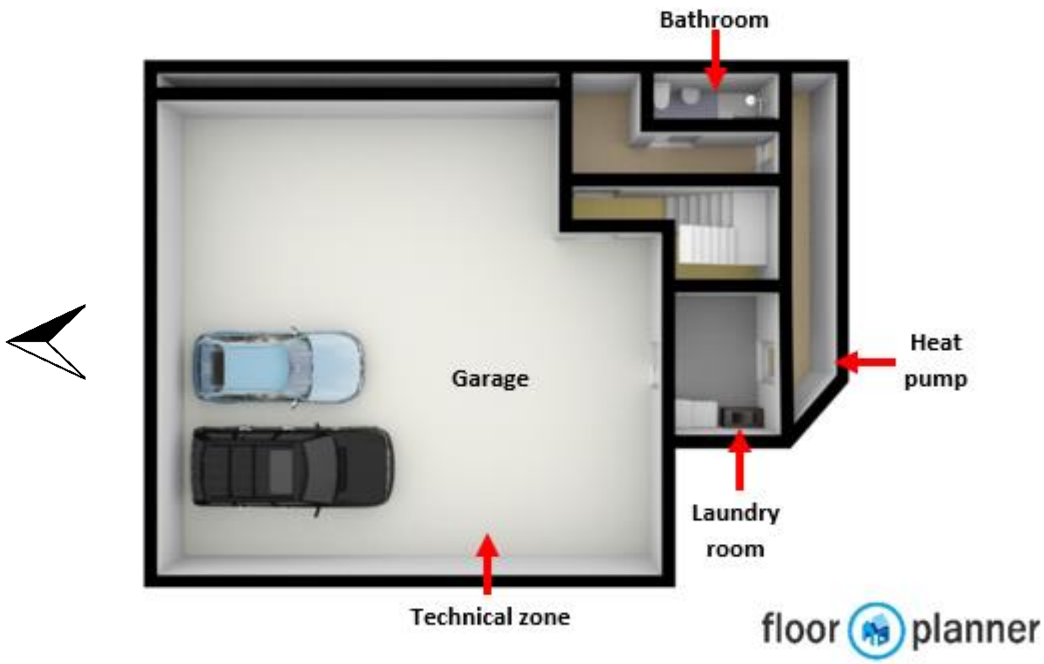

Figure 25. Floor (-1) view as designed in Floor Planner

PARKING AREA

The townhouse contains an interior parking area with sufficient space for 2 cars. It features an automatic garage door, as well as a sensor for opening the door and managing the lighting system (Figure 26). A system for charging electric cars is also present.

Figure 26. Parking area (left), garage door sensor (middle) and lighting systems (right)

TECHNICAL ZONE

This area of the building contains the battery for storage of energy from the photovoltaic panels, a control panel, and the pool pump (Figure 27).

Figure 27. Main view of technical zone (left) and various installations

An Ampere Square 63 6kWh battery is also installed in the technical zone, storing the energy produced by the photovoltaic panels installed on the roof of the building.

LAUNDRY ROOM

The noisiest appliances were relocated to the (-1) level to avoid the propagation of noise. The room contains a class A++ washing machine and clothes dryer, and also houses components of the solar collector system such as the storage tank and an expansion tank (Figure 28).

Figure 28. From left: view of the laundry room, energy efficient appliances, solar collector system components

BATHROOM

The bathroom on this floor is relatively small, comprised of only a sink, toilet and shower. Despite its small size, the bathroom is equipped with a Soler&Palau SILENT-100 DESIGN ECOWATT Series vent. The same model of sinks, toilets, showers and vents is used throughout the entire dwelling. On the hallway leading to the bathroom, a small window is installed to allow for natural lighting from the outside despite this floor being located underground. The stairs leading to this floor as well as up to floor (1) are equipped with sensor-controlled lighting systems.

Floor (0) description

Figure 29. Floor (0) view as designed in Floor Planner

HALLWAY

This area of the building contains the main panel for the domotics system installed, as well as a control panel and the wireless system (Figure 30).

Figure 30. Domotics system panel, control panel and Wi-Fi modem

KITCHEN

Figure 31. Townhouse 307 kitchen views

In order to reduce environmental emissions, the kitchen (Figure 31) is only equipped with electrical appliances, including the stove and oven. Moreover, the appliances used are energy efficient (for example, class A++ refrigerator). Examples can be seen in Figure 32 below.

Figure 32. Electrical instead of gas-based (left) and energy efficient appliances (right)

LIVING ROOM

Figure 33. Townhouse 307 living room views

The living room design takes full advantage of natural lighting, opening to the exterior on 2 sides of the building, with the western wall made completely of glass (Figure 33). This also allows for a view towards the terrace and garden, as well as the pool and the green area beyond.

STUDY

Figure 34. Townhouse 307 study view

The study (Figure 34) incorporates a similar design to that of the living room, with a full glass wall facing the western side. Lighting is done by means of lamps using LED lightbulbs.

BATHROOM

The floor (0) bathroom is fully equipped with a sink, shower and bathroom; it also features the same vent model as in the bathroom on floor (-1) – see Figure 35.

Figure 35. Townhouse 307 bathroom on floor (0)

Floor 1 description

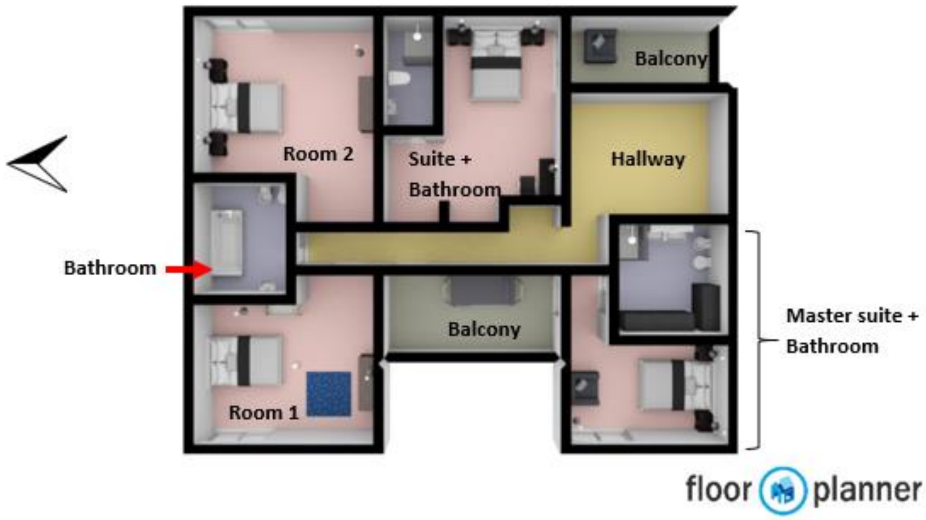

Figure 36. Floor (1) view as designed in Floor Planner

MASTER SUITE + BATHROOM

The master suite contains the basic necessities, such as the bed, nightstands, armchair and desk lamps which can be observed on the left and middle of Figure 37. From the same figure it can also be observed that a little over half of the western wall in the room is covered in windows. As it faces the other way from the east, sunlight is not bothersome in the mornings, but the room allows for natural lighting throughout the day. There is also a glass door opening up to the balcony shown on the right of Figure 37; this allows for easy and efficient natural ventilation.

Figure 37. Townhouse 307 master suite (left and middle) and terrace (right)

As an en-suite, the room comes equipped with its own bathroom, which is merged with a wardrobe area (Figure 38). Lighting is done by means of LED lights, and a skylight is also installed above the shower to allow for natural lighting.

Figure 38. Townhouse 307 master suite bathroom (left) and wardrobe (right)

SUITE + BATHROOM

The suite is designed in a similar fashion to the master one, consisting of the same furniture (Figure 39) and including its own bathroom. The bathroom also presents energy efficient lighting, as well as a skylight installed above the shower area.

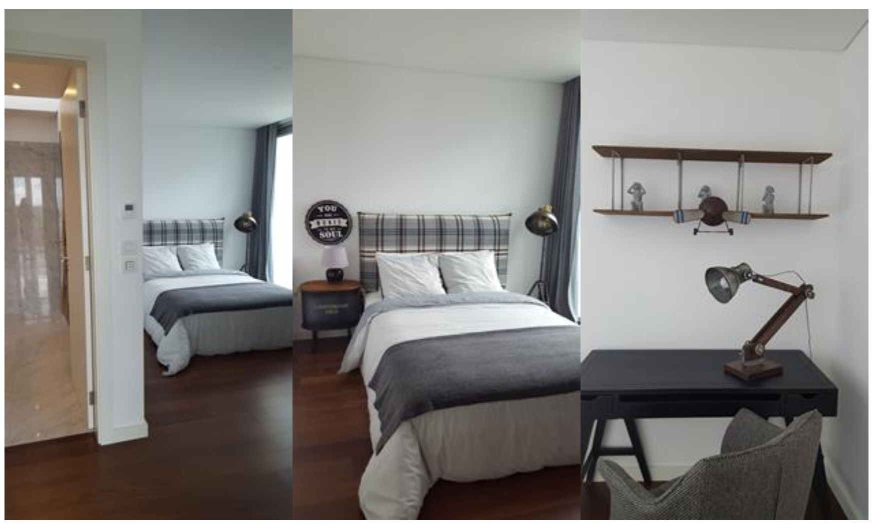

Figure 39. Townhouse 307 suite

ROOM 1 & ROOM 2

Aside from the two suites, the townhouse also consists of two individual rooms, which share a common bathroom. Room 1 (Figure 40) is designed as a children's room, containing a single bed, a crib and a play area. The use of a non-LED ceiling lamp was observed.

Figure 40. Townhouse 307 Room 1

By contrast, Room 2 (Figure 41) presents as a room more fitting for a teenager, with a simple bed and wardrobe. Lighting is done by means of LED lamps.

Figure 41. Townhouse 307 Room 2

BATHROOM

As previously mentioned, the two simple rooms share a common bathroom (Figure 42), which is similar to the other bathrooms of the townhouse, with the exception of a bath being installed rather than a shower.

Figure 42. Townhouse 307 Shared bathroom

Annex 2. Townhouse modelling

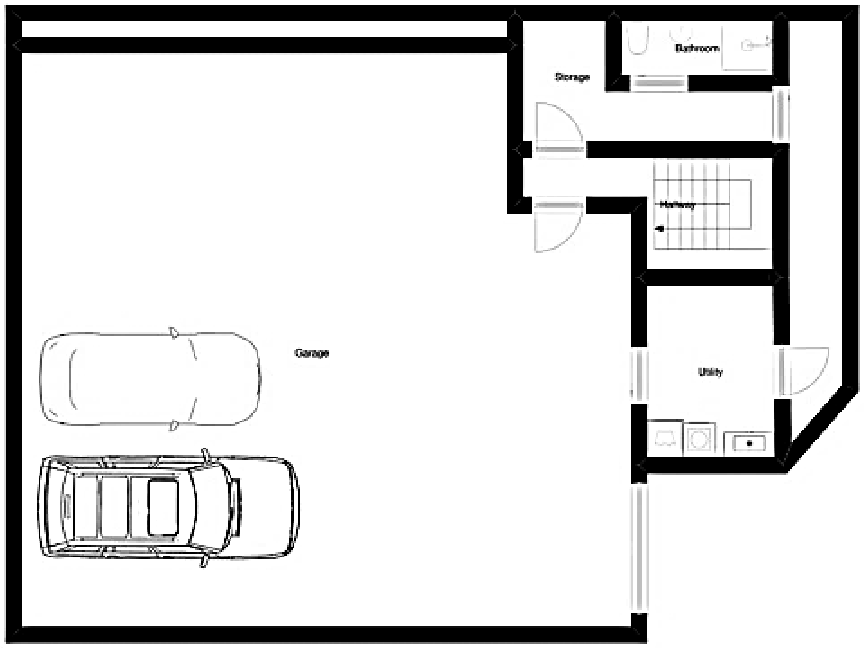

Figure 43. Schematic floorplan of floor (-1)

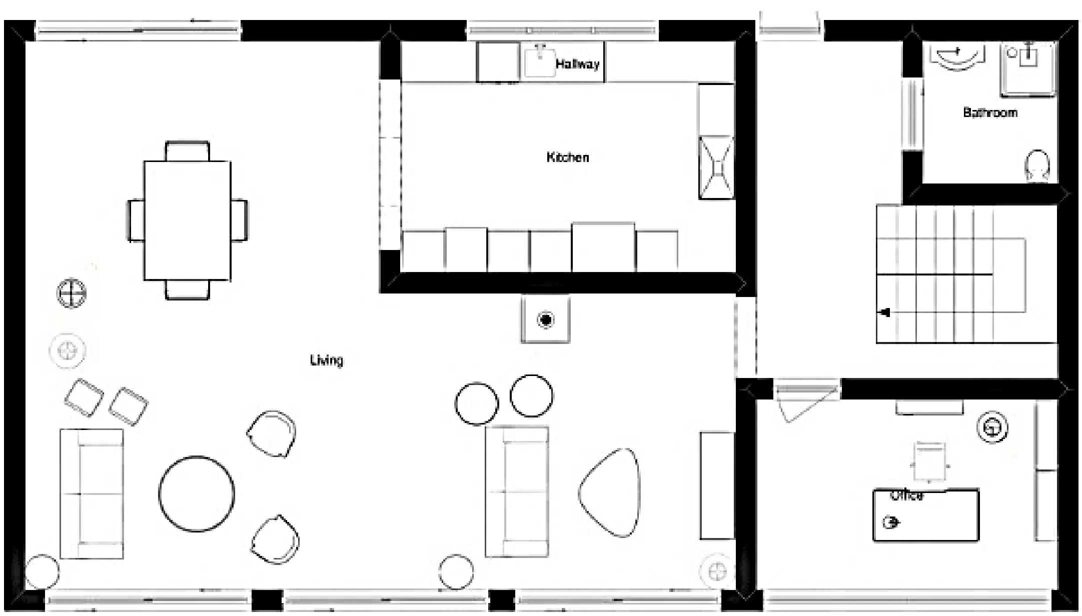

Figure 44. Schematic floorplan of floor (0)

Figure 45. Schematic floorplan of floor (1)

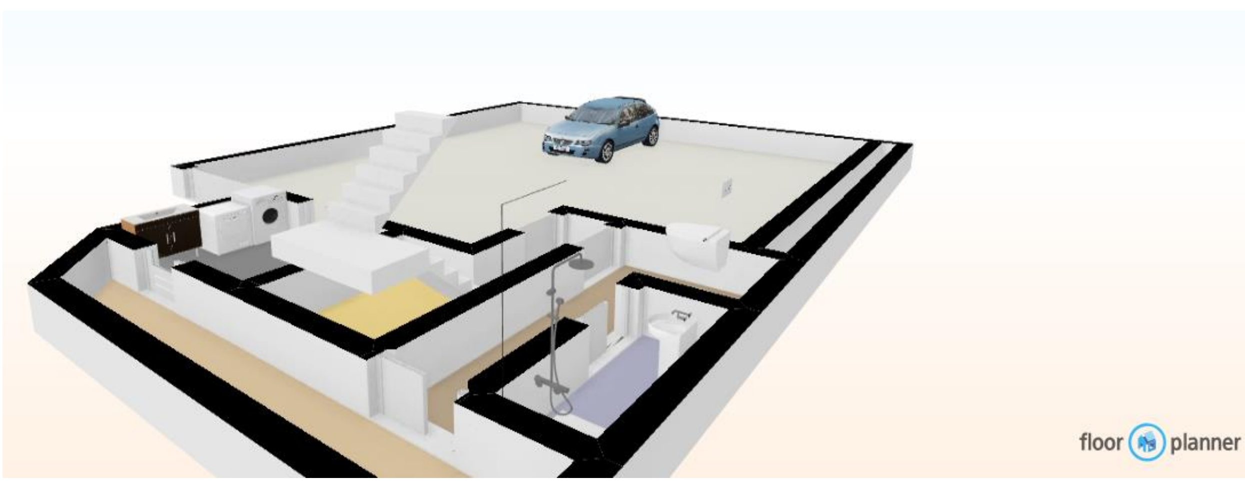

Figure 46. South-East view of floor (-1)

Figure 47. West view of floor (0)

Figure 48. East view of floor (0)

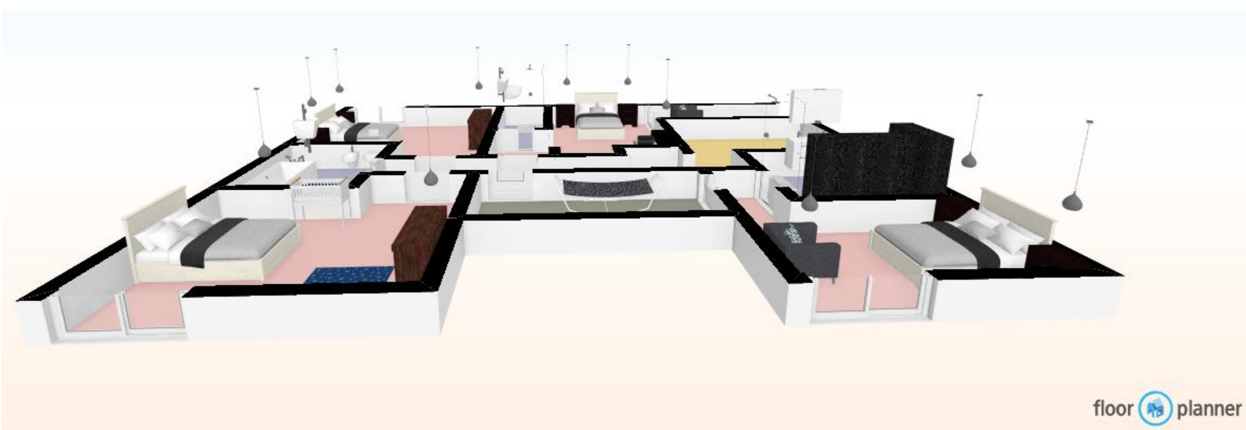

Figure 49. West view of floor (1)

Figure 50. East view of floor (1)

Annex 3. Appliance consumption

Table 23. Appliance consumers in Townhouse 307 (part 1)

Room	Appliance	Brand	Model	Power	No of units	Schedule	Daily consumption
				[kW]	[-]	[h/day]	[kWh]
P	Car charging	Renault	Zoe	3.60	1	8.0	28.80
	Car gate	Hornmann		0.06	1	0.2	0.01
	Garage door	Hornmann	LPU 40	0.20	1	0.2	0.03
TZ	Heat pump	Daikin		3.42	1	2.0	6.84
	Sewage pump	Lowara	DOMO 7VXT	0.49	2	0.5	0.49
	Rainwater Pump	Lowara	DLF 90	0.53	2	0.5	0.53
	Lawnmower	Bosch	Rotak 40	1.70	1	0.1	0.17
LR	Washing machine	Siemens	IQ500 - WM10T408ES	0.50	1	0.8	0.40
	Clothes dryer	Bosch	WTG86260EE	2.80	1	0.5	1.40
	Iron	Phillips	GC 4516/20	2.40	1	0.3	0.60
B1	Ventilation unit	SOLER & PALAU	SILENT-100 DESIGN ECOWATT Series	0.01	1	0.3	0.00
K	Exhaust hood	Bosch	DWB09W651	0.25	1	1.0	0.25
	Induction plate	Bosch	PIT851F17E	6.00	1	1.0	6.00
	Electric oven	Bosch	HBA43S452E	3.38	1	0.5	1.69
	Microwave	Bosch	HMT75M654	1.27	1	0.5	0.64
	Refrigerator	Bosch	KIR81AF30	0.09	1	8.0	0.72
	Freezer	Bosch	GIN38P60	0.12	1	8.0	0.96
	Dishwasher	Siemens	IQ500 - SN66M039EU	0.80	1	0.8	0.60
	Vacuum cleaner	Hoover	SJ WWR6 011	0.08	1	0.3	0.02
	Toaster	Morphy Richards	242026	1.00	1	0.2	0.20
	Coffee machine	Nespresso	Inissia Black de´longhi EN80	1.26	1	0.5	0.63

Table 24. Appliance consumers in Townhouse 307 (part 2)

Room	Appliance	Brand	Model	Power	No of units	Schedule	Daily consumption
				[kW]	[-]	[h/day]	[kWh]
L	Television	LG	60UH	0.08	1	5.0	0.40
	Mobile phone/tablet			0.05	4	1.0	0.20
	Vacuum cleaner	Rainbow	Illuminate	1.80	1	0.5	0.90
ST	PC	Apple	Macbook Pro 13"	0.20	1	4.0	0.80
B2	Electric towel rail	Foursteel	SG800E	0.90	1	0.5	0.45
	Ventilation unit	SOLER & PALAU	SILENT-100 DESIGN ECOWATT Series	0.01	1	0.3	0.00
MS	Hair dryer	Parlux	3200 compact	1.90	1	1.0	1.90
B3	Electric towel rail	Foursteel	SG800E	0.90	1	0.5	0.45
	Ventilation unit	SOLER & PALAU	SILENT-100 DESIGN ECOWATT Series	0.01	1	0.3	0.00
B4	Electric towel rail	Foursteel	SG800E	0.90	1	0.0	0.00
	Ventilation unit	SOLER & PALAU	SILENT-100 DESIGN ECOWATT Series	0.01	1	0.0	0.00
B5	Ventilation unit	SOLER & PALAU	SILENT-100 DESIGN ECOWATT Series	0.01	1	0.3	0.00
P2	Pool pump	Astral	Victoria Plus	0.74	1	7.5	5.55
						Total consumption [kWh/day]	**61.62**
						Total consumption [kWh/year]	**22,491.72**
						Adjusted total consumption to allow for 10% holiday time [kWh/year]	**20,242.55**

Annex 4. Lighting consumption

Table 25. Lighting consumers in Townhouse 307 (part 1)

Room	Lighting type	Brand	Model	Power [kW]	Units [-]	Total power [kW]	Schedule [h/day]	Consumption [kWh/day]
P	Suspended lighting	Climar	SPY Recessed 55 LED	0.05	6	0.282	0.4	0.113
LR	Suspended lighting	Climar	SPY Recessed 55 LED	0.05	1	0.050	0.5	0.025
B1	Square ceiling light	HiB	Inertia LED	0.02	1	0.018	0.2	0.003
K	Recessed spotlight		PCE-DL7W	0.01	8	0.056	5.0	0.280
L	Table lamp	IKEA	RYET LED bulb E27 400 lumen	0.01	3	0.015	6.0	0.000
	Netting lamp	Industry & Co.	Round Filament Light Bulb - 40W	0.04	2	0.080	6.0	0.090
	Ceiling lamp	Industry & Co.	Round Filament Light Bulb - 40W	0.04	2	0.080	6.0	0.096
ST	Wall lamp	IKEA	RYET LED bulb E27 400 lumen	0.01	1	0.005	2.0	0.096
	Desk lamp	IKEA	RYET LED bulb E27 400 lumen	0.01	1	0.005	2.0	0.010
B2	Surface profile lighting	Climar	SPY Surface 55 LED	0.03	1	0.030	0.3	0.010
	Recessed spotlight		PCE-DL7W	0.01	2	0.014	0.3	0.009
H2	Recessed spotlight		PCE-DL7W	0.01	4	0.028	0.2	0.004
	Ceiling lighting	Climar	SPY Trimless 33 LED	0.05	1	0.052	0.2	0.004
MS	Table lamp	IKEA	RYET LED bulb E27 400 lumen	0.01	3	0.015	2.0	0.008
B3	Recessed spotlight		PCE-DL7W	0.01	3	0.021	1.5	0.030
	Recessed spotlight		PCE-DL7W	0.01	3	0.021	1.5	0.032
	Surface profile lighting	Climar	SPY Surface 55 LED	0.03	2	0.060	1.5	0.032
SU	Table lamp	IKEA	RYET LED bulb E27 400 lumen	0.01	2	0.010	0.0	0.000
	Standing lamp	Industry & Co.	Round Filament Light Bulb - 40W	0.04	1	0.040	0.0	0.000
B4	Surface profile lighting	Climar	SPY Surface 55 LED	0.03	1	0.030	0.0	0.000
	Recessed spotlight		PCE-DL7W	0.01	2	0.014	0.0	0.000
R1	Ceiling lamp	IKEA	RYET LED bulb E27 400 lumen	0.01	1	0.005	4.0	0.020
	Standing lamp	Industry & Co.	Round Filament Light Bulb - 40W	0.04	2	0.080	4.0	0.064
R2	Desk lamp	IKEA	RYET LED bulb E27 400 lumen	0.01	3	0.015	4.0	0.060
B5	Surface profile lighting	Climar	SPY Surface 55 LED	0.03	1	0.030	2.0	0.060
	Recessed spotlight		PCE-DL7W	0.01	2	0.014	2.0	0.028

Table 26. Lighting consumers in Townhouse 307 (part 2)

Room	Lighting type	Brand	Model	Power [kW]	Units [-]	Total power [kW]	Schedule [h/day]	Consumption [kWh/day]
OTHER	Recessed spotlight		PCE-DL7W	0.01	3	0.021	5.0	0.105
	Square ceiling light	HiB	Inertia LED	0.02	5	0.090	0.5	0.045
							Total consumption [kWh/day]	**2.337**
							Total consumption [kWh/year]	**852.9**
							Adjusted total consumption [kWh/year]	**767.6**

Annex 5. PV panel specifications

The PV system consists of 13 GENIUS 4BB 250 W, the main characteristics of which were taken from a document provided by Prof. Manuel Guilherme Caras Altas Duarte Pinheiro and summarized below in Table 27 and Table 28. The battery characteristics summarized in Table 29 were also taken from the documents provided by the professor.

Table 27. Electrical specifications for PV

Nominal power	[Wp]	P_{NOM}	250
Positive Power Tolerance	[W]		0-5
MPP Current	[A]	I_{MPP}	8.32
MPP Voltage	[V]	V_{MPP}/U_{MPP}	30.0
Open Circuit Voltage	[V]	V_{OC}/U_{OC}	37.3
Short Circuit Current	[A]	I_{SC}	8.91
Module Efficiency	[%]	η	15.4
NOCT	[°C]		46±2

Table 28. Mechanical specifications for PV

Dimensions	1,640 x 992 x 40 mm
Weight	18.5 kg
Cell type	Polycrystalline
Number of cells per module	60 (6 x 10)

Table 29. Ampere 6 kWh Square 63 battery specifications

Ambient Temperature Range	[°C]		0-40
Size	[mm]		1,050 X 1,050 X 180
Weight	[kg]		100
Nominal Energy Storage Capacity	[kWh]		6
Maximum Depth of Discharge	[%]	DoD	95
Battery type			Li-Ion
Life cycle			>6,000
Calendar life			>15 years

Annex 6. Solar collector specifications

Table 30. WarmSun (FKC-2W) solar collector specifications [66]

Assembly mode		Horizontal
Dimensions	[mm]	2,017 x 1,175 x 87
Total area	[m^2]	2.37
Opening floor area	[m^2]	2.25
Absorber area	[m^2]	2.18
Rated flow	[l/h]	50
Optical efficiency		0.77
Primary loss coefficient	[W/m^2K]	3.871
Secondary loss coefficient	[W/m^2K]	0.012

Annex 7. Final scenario results

Table 31. Final results of scenarios

Parameter	Unit	Current status	Scenario 1 - LED	Scenario 2 - Collector	Scenario 3 - PV	Scenario 4 – LED+Collector	Scenario 5 – LED+PV	Scenario 6 – LED+PV+Collector
Lighting consumption	[kWh/year]	768	431	768	768	431	431	431
Appliances consumption	[kWh/year]	20,243	20,243	20,243	20,243	20,243	20,243	20,243
DHW consumption	[kWh/year]	3,396	3,396	3,396	3,396	3,396	3,396	3,396
PV generation	[kWh/year]	4,300	4,300	4,300	7,277	4,300	7,277	7,277
PV share	[%]	19	20	20	33	20	33	34
Collector generation	[kWh/year]	2,284	2,284	2,495	2,284	2,495	2,284	2,495
Collector share	[%]	67	67	73	67	73	67	73
Boiler consumption	[KWh/year]	1,112	1,112	901	1,112	901	1,112	901
Energy generated from gas	[kWh/year]	3,158	3,099	3,121	2,631	3,061	2,571	2,534
Emissions generated from gas	[kg CO_2/year]	632	620	624	526	612	514	507
Energy generated from coal	[kWh/year]	3,318	3,256	3,279	2,764	3,217	2,702	2,662
Emissions generated from coal	[kg CO_2/year]	1,128	1,107	1,115	940	1,094	919	905
Energy from co-generation	[kWh/year]	1,481	1,453	1,463	1,234	1,436	1,206	1,188
Emissions from co-generation	[kg CO_2/year]	400	392	395	333	388	326	309
Energy savings	[kWh/year]		336	211	2,977	547	3,313	3,524
	[% of current status]		1.376	0.864	12.197	2.242	13.575	14.441
	[kWh/lifetime]		16,797	10,540	148,837	27,359	165,656	176,218
	[€/year]		77	48	680	125	757	805
	[€/lifetime]		3,836	2,407	33,994	6,249	37,836	40,248
Investment	[€]		34	1,800	2,250	1,834	2,284	4,084
Rate of return	[years]		0.45	37.39	3.31	14.68	3.02	5.07
Operational Carbon savings	[kg CO2/year]		41	26	361	66	402	439
	[% of current status]		1.88	1.21	16.90	3.69	19.18	24.97
	[kg CO2/lifetime]		2,035	1,277	18,037	3,315	20,075	21,949
CO_2 emissions	[kg CO_2/year]	2,160	2,119	2,134	1,799	2,093	1,758	1,721

Note: The following assumptions have been made for performing the calculations:

- As the back-up boiler for DHW is electric, it was considered that its energy demand was the same value of energy not covered by the solar thermal collectors.
- The boiler cost was assumed from [74]
- The share of PV is assumed in reference to the lighting and appliance consumption, as well as the electric boiler requirements.