Life-Cycle Energy in Houses: Searching Low Energy Houses Operation. Case Study of Green Valley, Lisbon

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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 is generally the main focus for reducing the residential energy demand. It is defined as the energy consumed by a building during its lifetime, for heating, cooling, ventilation, lighting, appliances and domestic hot water purposes. The present work explores Operational Energy reduction in a Class A+ energy efficient single-family dwelling in Portugal.

The developed model compares the energy requirement and generation from renewable sources with the values specified in the building energy certificate for verification. It then analyzes various measures for further improvements in terms of energy and cost savings, as well as operational carbon reduction. The building is confirmed to be highly efficient, and three measures are found to be easy and affordable for implementation, which could reduce up to 3,524 kWh per year.

1. Introduction

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 issues. 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.

Consuming 40 % of final energy in Europe [1], 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. In the end, the scope is to reduce the energy consumption to the point where a building becomes either a Low Energy

Building (LEB) or a Nearly Zero Energy Building (nZEB).

By definition, LEBs are buildings with a low energy consumption [2], whereas nZEB are low energy buildings which cover a large share of their energy requirements from renewable energy systems installed on-site [3].

2. Literature review

The energy consumed over the duration of a building life-cycle can be simply divided into Embodied Energy, covering the stages of material production, transport, construction, and disposal, and Operational Energy, the amount of primary energy that a building consumes over its lifetime for heating, cooling, lighting, appliances and domestic hot water use.

Of the processes, operational energy related emissions are *'regarded as the largest contributor to the life-cycle impacts'* [4], amounting to as much as 80-90% *'in conventional buildings and 40-60% in LEBs'* [5].

An initial literature review was conducted to observe various single-family dwellings' operational energy consumption according to parameters such as useful surface of building, materials used, location and lifespan.

A total of 22 journal articles were selected as relevant from an initial pool of 64, and their total case studies summed up 45 various buildings, which were analyzed in terms of characteristics versus operational energy parameters, as well as to observe the methods used for operational energy reduction. The most notable have been found to be:

- Building in height rather than ground surface might lower heating requirements, as found by Adalberth (1997) [6];
- Use of energy efficient appliances may reduce up to 40% of electricity consumption according to Blanchard & Reppe (1999) [7];
- Replacement of inefficient lightbulbs with more efficient ones was proposed by Blanchard & Reppe (1999) [7];
- Improving building envelope can have significant reductions in space heating and cooling consumption, as found by Blanchard & Reppe (1999) [7], Winther & Hestness (1999) [8], Fay et al. (2000) [9], Keoleian et al. (2001) [10], Citherlet & Defaux (2007) [11].
- Installing a heat pump was found by Dahlstrøma et al. (2012) [12] to reduce 40% of energy consumption, and 30% of emissions in a passive house.

3. Case study

The selected case study is part of the Belas Clube de Campo residential area, which was initiated in the 1990's. The neighborhood is comprised of three main stages, two of which have already been built. The third one is still a work in progress and is so far set to incorporate 14 townhouses and an apartment building.

One of the 14 single-family, three-floor townhouses (two above ground and one basement) has been chosen for analysis (Figure 1).

Figure 1. Townhouse 307 on the right and adjoining townhouse on the left

Figure 2. Floorplan of floors 0 (left) and 1 (right) of the building

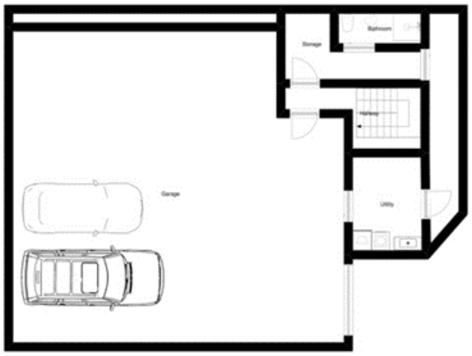


Figure 3. Floorplan of basement

Built mainly of concrete, the townhouse is semi-detached, and is built on three levels, which can be observed in Figure 2 and Figure 3, as designed in the FloorPlanner software.

The basement consists of a garage area able to fit 2 cars and equipped with EV charging, as well as a laundry room, a bathroom and installed equipment for the heat pump, solar collectors, PV panels and pumps. The ground floor (0) consists of a kitchen, bathroom, living room and study, while floor (1) contains two suites equipped with their own bathrooms, as well as two normal rooms sharing a common bathroom.

The townhouse is certified as a LiderA class A+ energy building, where 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'* [13].

This certification is obtained due to the energy efficiency methods implemented in the design of the building [14], such as:

- Use of energy efficient and all-electric appliances;
- Use of mostly LED lighting systems;
- Use of large windows on W and E façades of the building to allow for natural light as much as possible;
- Use of natural ventilation;
- Rainwater collection and use of flow-reducing installations for sanitary use.
- Use of 13 GENIUS 4BB 250W PV panels for electricity generation, as well as an Ampere Square 63 6kWh battery for storage;
- Use of 2 Vulcano FKC-2W flat-plate solar collectors for hot water production;
- Use of a 15 kW Daikin ERLQ016CAV3 heat pump which covers 100% of space heating requirements.

4. Current status

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

- Yearly lighting consumption = 768 kWh/year;
- Yearly appliance consumption = 20,243 kWh/year;
- Yearly DHW requirements = 3,396 kWh/year.

It was initially assumed that production of DHW was carried out by using boiler with a consumption of 3,396 kWh/year.

Based on these values, an initial determination of CO_2 emissions was carried out by assuming no renewable energy generation for the chosen location. For this, the total primary energy supply of Portugal in 2018 (Figure *4*) was used, and an operational carbon value of 2,958 kg of CO_2 was obtained.

A specific CO_2 emissions value of 0.2 kg/kWh was used for natural gas, 0.34 for coal and 0.27 for co-generation by assuming a 50/50 use of the previous two fossil fuels [15].

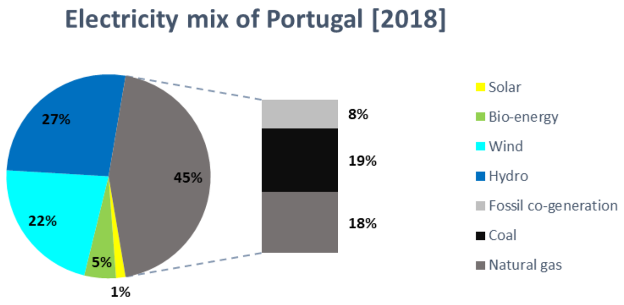


Figure 4. Electricity mix of Portugal (2018) - Adapted from *[16]*

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

- PV panels
- Solar collectors

The analysis of PV and collector yield was carried out by using local solar irradiation values, as well as the specifications of the particular models used in the location.

The following steps and formulas were used in determining the PV and collector yearly yield:

4.1. PV system yield

Solar irradiation data was collected from the European Commission Joint Research Centre (JRC) [17], and a sensitivity analysis was carried out between three different methods to obtain a common value:

a) Method 1

$$\mathbf{E = A * r * G * PR} \tag{1}$$

Where

- E = Energy generated [kWh];
- A = Array total surface [21.2 m^2];
- r = Solar panel efficiency [15.4 %];
- G = Solar irradiation [$kWh/m^2/day$];
- PR = Performance coefficient (assumed as default value, 0.75).

b) Method 2

$$\mathbf{E = \ G * PR * P * no\ of\ days} \tag{2}$$

Where

- E = Energy generated [kWh];
- G = Solar irradiation [$kWh/m^2/day$];
- PR = Performance coefficient (assumed as default value, 0.75);
- P = Array power [kW].

c) Method 3

A third method made use of the same European Commission Joint Research Centre (JRC) [17] 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 value of 4,270 kWh/year.

After obtaining a 4,309, 4,300 and 4,270 kWh/year value, a general value of 4,300 kWh per year generation was assumed for the PV system.

4.2. Solar collector system yield

A scoping study conducted in 2015 at the University of Strathclyde in the UK produced the calculation method [18] used for determining the solar thermal energy production for the case study analyzed. In this study, the following formula (3) was used to define the solar input of solar thermal collectors:

$$\mathbf{Q_s} = \mathbf{A_{ap}} * \mathbf{\eta_0} * \mathbf{S} * \mathbf{Z_{panel}} * \mathbf{UF} * \mathbf{f_1} * \mathbf{f_2} \qquad (3)$$

Where

- Q_s = Solar input [kWh/year]
- A_{ap} = Aperture area of collector [4.5 m^2]
- η_0 = Zero loss collector efficiency [77%]
- S = Total solar radiation on collector [1,725 kWh/m^2/year]
- Z_{panel} = Overshading factor for the solar panel [1, due to lack of obstructions]
- UF = Utilization factor [0.43]
- f1 = Collector performance factor [0.79]
- f2 = Solar storage volume factor [1.1]

The values used in the formula were determined by following the steps described in the study, with the following assumptions:

- A_{ap} and η_0 were taken from the collector specifications;
- S was taken as 1,725 kWh/m^2/year after considering several possibilities [19] [20] [21];
- The panels are placed horizontally on a flat rooftop, with no obstructions;
- The DHW storage tank has a capacity of 300 liters, and the daily demand is 178 liters for a family of 4 (160 for regular use, and 18 assumed for clothes and dishwashing)

In the end, a total value of 2,284 kWh/year energy generation was determined to be obtained from the solar thermal collectors installed.

4.3. Operational carbon

By eliminating the share of energy covered by renewables from the calculations (19% for electricity and 67% for DHW production), the remaining energy was considered to be covered by using electricity from the grid, and the new operational carbon obtained was 2,160 kg CO_2/year (27% reduction from the baseline case).

5. Improvement scenarios

The improvements identified during the literature review, as well as others were sorted into 5 main categories, which can be found in Figure 5 below.

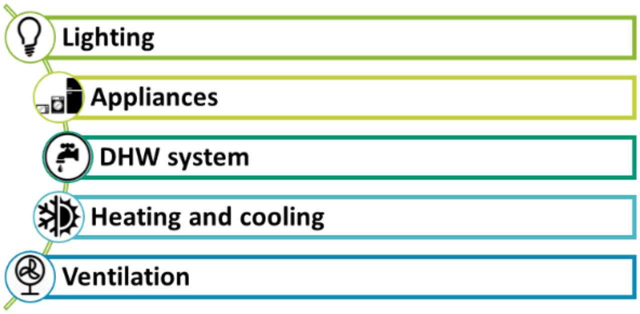


Figure 5. Categories used for improvement assessment

Each of the proposed methods was then analyzed to see if it was already in use in the townhouse design or viable to be implemented. In the end, the following scenarios were developed:

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

Figure *6* below shows the proposed location for addition of solar collectors and PV panels.

Figure 6. Proposed installation of PV panels

5.1. Lighting scenario

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 [22], 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 [23], the investment required for this improvement is 34.3€.

5.2. Collector scenario

By assuming the hot water storage tank 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.

5.3. PV scenario

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.

For the proposed layout, the initial 4,300 kWh/year production from PV panels becomes 7,277, which is an almost 70% increase of energy generation. The system also covers 5% more of the energy requirements for lighting and appliances, for an estimated investment of 750 €. As the actual product cost could not be obtained, an estimation was done based on the various 250W polycrystalline panels available on the market.

5.4. Combined scenarios

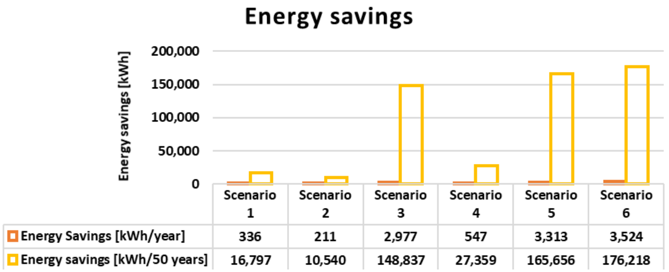
Several combined scenarios were also considered based on the three previously described:

a) Lighting + solar collectors;
b) Lighting + solar PV;
c) Lighting + solar collectors + PV.

6. Results and discussion

ENERGY SAVINGS

As can be observed in the graph below (Figure *7*), 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.



	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5	Scenario 6
□ Energy Savings [kWh/year]	336	211	2,977	547	3,313	3,524
□ Energy savings [kWh/50 years]	16,797	10,540	148,837	27,359	165,656	176,218

Figure 7. Yearly and lifetime energy savings for all scenarios

OPERATIONAL CARBON SAVINGS

As the townhouse is already highly efficient, CO2 emission savings are understandably low, as represented in Figure 8. When combining all three scenarios, a maximum saving of around 439 kg per year is observed, and 22 tons for the entire lifetime considered.

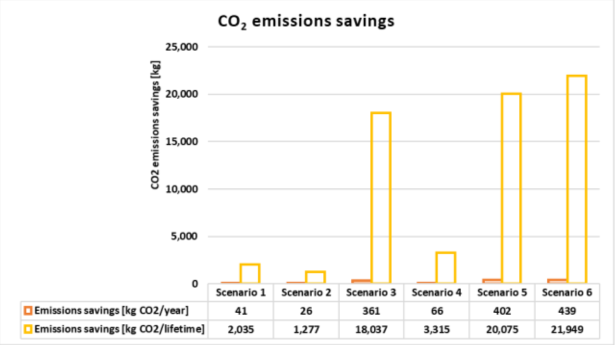


Figure 8. Yearly and lifetime emissions savings for all scenarios

COST SAVINGS

By using the energy cost for households in Portugal as 0.2284 €/kWh [24], 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 9), 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.

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.

7. Conclusions

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 this paper, 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.

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.

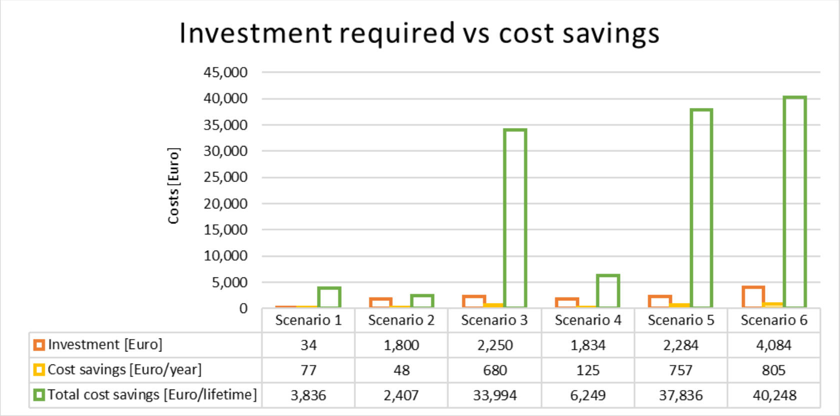


Figure 9. Yearly and lifetime cost savings versus investment for all scenarios

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