Autonomous energy system planning for the Vale Santo Antonio district in Lisbon

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The objective of this thesis is to propose an energy system that allows the area of Vale de Santo António in Lisbon to be self-sufficient from an energy point of view. As a starting point, it is necessary to forecast the consumption of buildings in 2050, based on the analysis of scenarios for the evolution of energy systems in Portugal. Then, an urban energy modeling tool (UBEM), the City Energy Analyst (CEA), is used to make the consumption model of the area under analysis and create consumption scenarios. After, taking into account the expected evolution of energy systems towards decarbonization, different measures of energy efficiency and energy generation are tested to verify the potential for self-sufficiency. The results are based on the analysis and comparison of the different output elements obtainable by CEA. In particular, the demand for energy decreases sharply, with cuts of up to 70% on the final consumption of the neighborhood, satisfying the self-sufficiency objectives for 2050 on residential. At the same time, in the most optimistic scenario, emissions are reduced by 40%, however, a result not as satisfactory as energy consumption. On the other hand, thanks to the renovation, thermal comfort is guaranteed to all buildings in the winter season, one of the most serious problems to face for the neighborhood and Portugal. Thus, CEA behaves as a modeling tool that, despite requiring a high, and often inaccessible, amount of data, could provide useful preliminary support for the energy planning of the district.

Keywords: UBEM, self-sufficiency, renewable energy systems, City Energy Analyst, energy efficiency.

1. Introduction

The global population, currently about 7.8 billion, is exponentially growing. We take the energy for granted, but we should keep in mind that the situation will be much different in few years. Worldwide energy supply is still based on fossil fuels such as coal, natural gas and finally oil, major actor among the greenhouse gas producers, which will bring disastrous consequences on our planet without an immediate brake. In the future, the only possibility for a clean and much more populous planet is a society based on the net-zero energy.

The case study is in Vale Sant Antonio (VSA) is a district of the old part of Lisbon municipality. A huge percentage of the district, 29%, will be urbanized with new buildings in a few years, investing an area of 51,551 m^2. They will be mostly multi-residentials, like the rest of the old constructions, basically prior to the 70s [1] and they all need to be self-sufficient. The first step was to understand if it is possible to contribute to this effort by using a tool to simulate the energy system - an urban building energy modeling (UBEM), in order to define the best solutions. The study started from a current energy scenario, which needed to be analyzed, uploaded on the software, and optimized, to propose an autonomous district.

1.1. Autonomous systems

Autonomous system is defined as a complex of autonomous buildings, or better known as Zero-energy buildings. According to EU “nearly zero-energy building” means a building that has a very high energy performance. 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.

In Europe there is a large variety of concepts and examples for nearly zero-energy buildings. There are non-governmental examples putting emphasis on different aspects (like the “ZeroHaus” or “Passivhaus”, Passive House in English) as well as government-initiated programs which usually focus on the buildings’ efficiency (e.g. Minergie from Switzerland). In most cases the heating demand is drastically reduced by following the Passive House concept; in some cases, electricity use by lighting and appliances is included. On-site power generation from renewables, usually from PV, balances demands of heat pumps, other HVAC systems. In addition, the house insulation play a key role.

Modelling a future scenario, which aims to improve strongly the thermal comfort keeping as low as possible the consumption, as well as the GHG emission. The challenge to face is to build a system capable to guarantee thermal comfort, cutting the emissions and fossil fuel dependency. These measures will require considerable engineering and customization efforts for each installation. The UBEM proposed, called City Energy Analyst (CEA), is capable to help in this effort. The novelty of the work consists in using this tool to define the retrofit strategies and energy generation solutions for the district in order to achieve the self-sustainability.

2. Energy’s panorama

2.1. World overview - cities

Around 55% of the world’s population lives in urban areas, a proportion that is expected to increase to 68% by 2050. Occupying less than 2 percent of the Earth’s land, the cities account for 60-80% of global energy consumption and 75% of carbon emissions.

Into the cities, buildings have the highest consumption compared to the other consumption sectors and only the household appliances energy use is nearly 15% of global final electricity demand [2]. So, much of the reduced energy demand will occur in buildings, in both the residential and services sectors, which together are responsible for 40% of total energy consumption. Both the UN and the EU Commission are dealing to spread awareness about. They are adopting new targeted building policies, supporting the principles stated by the Paris Agreements in 2016. [3] [4] [5].

2.2. Portugal

In 2017 Portugal consumed a total of 16 420 ktoe of final energy consumption [6]. Among these consumptions, the buildings were about the 28.6 %[domestic (16.4%), services and commerce(12.2%)] [7].

Among the domestic services, it is noteworthy the energy consumption for the space heating, which corresponds to 8% of the total consumption of energy in 2010. Electricity was one of the main sources of energy used for the indoor heating, however the diesel and the wood still represent important shares of energy consumption in this type of use (figure 1)

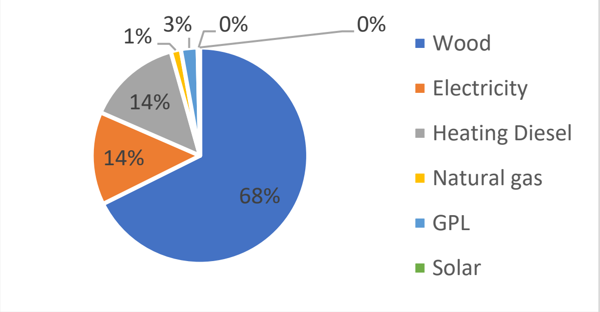


Figure 1. Distribution of energy consumption for ambient heating by source type (Portugal, INE 2010)

Portugal has the possibility to cut significantly these fossil fuels, thanks to the renewable sources. Presently the country generates about 50% to 60% of electricity from renewable sources. The percentage of incorporation of renewable energies in heating and cooling, according to the long-term strategy for carbon neutrality of the Portuguese economy by 2050, should reach at least 70% (heating and cooling respectively 66% and 68%) [8][9][10].

Buildings are currently responsible for 5% of national GHG emissions and they still show high potential for reducing emissions, which will already start to be felt over the next two decades. Thus, emissions reductions are estimated for 2050 in the residential sector to be at -97% and -96% and 100% in the services sector (compared to 2005). Concluding, the expectations for 2050 involve a possibility of a decrease in energy consumption per m^2 in residential buildings from -7% to -20% compared to today.

2.3. Thermal comfort

Still, in 2020, thermal comfort in Portugal is not guaranteed in most of the buildings, despite the average high temperatures of the country area. A study by the University of Dublin revealed that Portugal ranks second in Europe among the countries that suffer most from the lack of thermal comfort. Probably because enormous potential remained untapped due to the widespread use of less-efficient technologies, a lack of effective policies, and insufficient investment in sustainable buildings [2].

Nevertheless, by 2050 in Portugal, an increase in residential thermal comfort is expected, both in heating and cooling (thermal comfort will triple in heating and double in cooling compared to the current situation). This increase in comfort comes from the electrification trend, the use of more efficient equipment (e.g. heat pumps), the increased use of insulation materials and higher rates of urban rehabilitation (e.g. replacement of windows). Insulation measures are estimated to reduce heating energy consumption by 26% by 2040 and around 50% by 2050 in the residential sector, so this increase in comfort does not result in a direct increase in final energy consumption[8].

3. The UBEM overview

Urban building energy modeling refers to the computational modeling and simulation of the performance of a group of buildings in the urban context. This category shows great heterogeneity and includes different types of tools and methodologies with different scopes. In general, the goal is to provide quantitative insights (e.g., annual or seasonal energy use and demand, potential of renewable power generation) to inform urban building design and operation, as well as energy policymaking. Urban building performance metrics include near-term operational efficiency (e.g., energy use and demand at the daily, monthly, and yearly time frames), short-term demand response (e.g., electric load shedding and shifting at the minute to hour time frame), long-term sustainability (e.g., GHG emissions, impacts of climate change on energy demand at the year to decade time frame), and event-driven resilience (e.g., impact of extreme weather events such as heatwaves and wildfire on energy use, power supply, and occupant health at the day time frame). UBEM can also estimate the potential of renewable power generation from photovoltaics (PV) or wind turbine systems located on rooftops or integrated into building facades. For electric vehicle (EV) charging that uses the building power system, UBEM can integrate the EV loads into the building's overall energy demand [11][12].

Among the several studies about UBEMs, two main modelling approaches are often identified: top-down and bottom-up. Bottom-up models calculate the energy consumption at a single building scale and then aggregate the results at different levels, considering an integrated framework. To perform properly, they need a large quantity of data whose availability may be hindered by privacy and other issues. However, they allow a very detailed simulation, since the more input a tool requires, the more accurate its analysis can be. This category is the one that has been analyzed, and it includes the tools that may better evaluate scenarios for current and future urban environments management and design[11][12].

3.1. UBEM Tools

Six different tools were studied among the physic-based, bottom-up models, since they are the most known, modern and their use showed a closer connection with the thesis work: CitySim, SimStadt, TEASER, UMI, CityBES, and CEA, tool which contributes for the work. However, the last three are the most comprehensive and recognized, they have been tested in many practical applications in different parts of the world.

3.1.1. UMI

The Urban Modeling Interface (UMI) evaluates the environmental performance of neighborhoods and cities with respect to operational and embodied energy use, walkability and daylighting potential. Focus users are urban designers and planners, municipalities, utilities, sustainability consultants and other urban stakeholders. It is one of the most relevant and used tool, since it offers beyond the standard functions, many further skills, estimating extra values like the level of walkability, bikeability, daylight and lifecycle among a district. Also, beyond the numerous applications in USA (Boston) [13] there were as well four UMI applications in Lisbon between 2016 and 2017. Based on the simulation engine EnergyPlus, running very detailed analysis, has some limitation of a personal computer, contrary to web-based software (CityBES) or tools which use simplified methods (SimStadt, CEA). [14][15]

3.1.2. CityBES

CityBES focuses on energy modeling, benchmarking and performance visualization of a city's building stock to support district or city-scale energy efficiency programs. CityBES uses and international open data standard, CityGML, to represent and exchange 3D city models. CityBES employs CBES to simulate building energy use and calculate savings from energy retrofits. CityBES, directly integrated with a GIS, allows the use of both the CityGML and GeoJSON. It includes further details of the buildings in addition to the ones available in standard geometry CityGML files. These advanced datasets are useful to easily run simulations on a large-scale, with various retrofit scenarios with performance and cost data for hundreds of thousands of buildings in U.S. cities. [12], [16], [17]

3.1.3. CEA

City Energy Analyst seems to be the most versatile tool, easily allowing simulations from the block-scale to the city-scale. It is directly integrated with a GIS. Being a plug-in for ArcGIS is able to directly analyze the data from GIS databases, when available. Differently than CityBES and UMI, that run the simulation with EnergyPlus, use simplified methods. Moreover, it offers energy demand/supply analysis for buildings at a district scale to support decision making of energy efficiency planning. Also, CEA has the most advanced model that considers the ambient heat potential (e.g. geothermic, lake water and source of waste heat) and solar potential. Besides, CEA allows the evaluation of Green House Gas (GHG) emissions through the LCA analysis, and it is provided with a tool to perform a cost-benefit. Especially useful for the work effort, the appliances and lighting, building envelope, HVAC systems, input settings which allow easily to perform a good building retrofits simulation. The CEA it has been subjected to numerous projects in the Swiss city of Zurich and in Singapore, where it has been and continues to be developed [18][19].

4. Current VSA analysis

The work aimed to build an energetic plan for the district using CEA, UBEM initially selected for this project. Beyond its positive reviews, numerous tests in this work have demonstrated how this choice could be reasonable, since CEA includes many skills when it's modelling neighborhoods, with a much larger range of outputs available, necessary for this analysis.

4.1. Inputs

The district inputs required, the description of their values and their source were properly provided. The majority or the inputs come from the CEA database. After the creation of the shape scenario zone, all the building geometrical features (“Archetypes” data) are calculated automatically, provided from GIS databases, the Geographic Identity System (figure 2).

Figure 2. CEA dashboard - one CEA random building selected

In a matter of seconds, we get a complete digital replica of buildings and streets in the area of interest, including other information ("Typology" data) such as: years of construction, use-type (residential, school, police, office, restaurant, library and food store). Moreover, Architecture data were required (type of construction, tightness level, then roof construction, shading system, external wall, floor, basement and window type). In addition, the Internal loads and the indoor comfort setting values were necessary. In parallel, we obtained metadata about energy supplies (heating, cooling and hot-water), HVAC system, surrounding buildings influence, schedule, carbon emissions, and costs. However, the whole database was implemented in Switzerland and Singapore, so a meaningful model of VSA needed various database changes. It required an accurate matching and completing with the ADENE data [20], especially for the energy system, which meshes several types of energy generation and emission.

4.2. Outputs

Among City Energy Analyst's output, the main significant results for the analysis consist in comfort results, energy consumption (final use), and emissions.

4.2.1. Comfort

The VSA current simulation showed a huge lack of thermal comfort in all the buildings as were the expectations. The absence of a reliable heating system is determinant, especially for the high thermal transmittance of surfaces. In each plot many points are representing the hours occupied by users in the building. Each building has its own chart; thus 110 different comfort plots are available as output. One random selected building chart is shown below (figure 4)

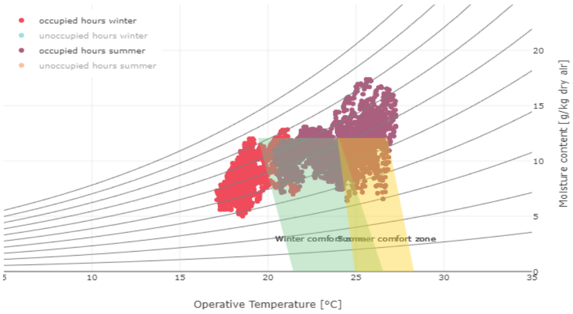
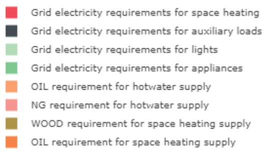


Figure 3. Building 1030 comfort chart

4.2.2. Energy demand

In order to figure out the CEA consumption of the VSA buildings, A large histogram presents the consumption of all buildings in the district, aiming to the Energy Use Intensity [kWh/m^2×yr], a clearer proof of which system is more energetic expensive and obsolete. From the district plot occurs a clear distribution of wood and oil-based buildings next to the highest intensities. In fact, as they turn to carbon-free sources, the intensity decreases proportionally (figure 33). ADENE 2010 data about Lisbon shows that occurred a net c energy intensity kWh/m^2×yr. a [21]. ADENE 2010 data collect Portugal, energy consumption in the domestic sector per capita was 3,489 kWh. Assuming a range that goes from 20 to 40 m2 as the average surface occupied by an inhabitant, the annual consumption could equal from 87 to 174 [kWh/m^2×yr]. Another estimation of the consumption [kWh/m^2×yr] could be obtained taking into account the total energy per house in Portugal (8.838 kWh) dividing by the average surface heated, according to the report (50 m2): the resulting demand is 172.4 [kWh/m^2×yr] [10]. However, looking at the Lisbon data from ADENE, the energy needs are lower, especially considering the 2006 multi-residential buildings, 80 [kWh/m^2 × yr], instead of the single houses, that reach about 130 [kWh/m^2×yr]. Furthermore, they are the closest values with CEA district demand, which goes from 50 to 150, 80 [kWh/m^2×yr] on average (Figure 4). The data obtained though CEA are so comparable with the real VSA.



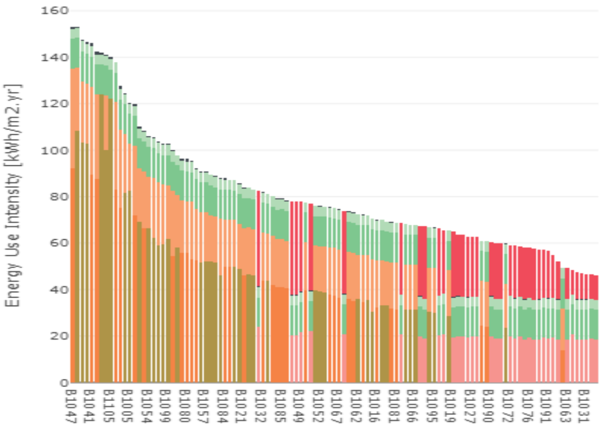


Figure 4. Energy final use intensity [MWh\m^2×yr] of the current VSA (CEA plot).

4.2.3. Emission

In the 2010 INE survey is reported that 21.5% of Portugal's total emission is associated with energy consumption in housing, 2.5 million tons of CO2-eq, and 628 kg CO2-eq/house [10]. Considering each house composed by 50 m^2, it equivales to 12.56 kg CO2-eq/m^2. Through the Life Cycle Analysis tool, CEA can evaluate the emissions (CO2-equivalent) and the result obtained is not far from the 2010 data emission per occupancy and then the emission per square meter. With an amount of 610 kg/year × pax, the first plot gave almost the same value of the emission per house from INE 2010 (628 kg CO2-eq/house); Although for each house we should consider more than one occupant, it can be considered a good result. By applying a normalization per net area, a second CEA graph, shows 16 kg CO2-eq/m2 × yr which kept little higher values trend, (ADENE = 12.56 kg CO2-eq/m^2). However, it remains a relatively low level compared to the European average level, which is around 27 kgCO$_2$eq/m^2× yr in 2008 [22].

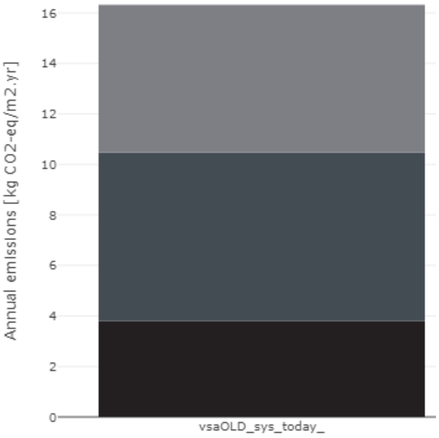


Figure 5. Annual emissions [kgCO$_2$eq/m^2×yr] of the current VSA normalized to net floor area.

5. VSA optimization measures

This future scenario aims to maintain the same buildings, basically keeping the same existing constructions uploaded by GIS and to refurbish them. It's so necessary to upgrade the inputs for each feature already introduced for the current scenario.

Following the principles for a sustainable district, the future scenario of Vale Sant Antonio was re-modelled through CEA. For setting the new district inputs, following the optimization measures, a significative reference is conferred from "Passive Houses". Other technical features have been provided from the European report Nearly Zero Emission Buildings (NZEB), which described many possible examples. However, no particular NZEB case is centered in Lisbon, so many comparisons with other cases City had to be studied, especially Catania, which represents the South Europe example [23][24].

New measures have been applied editing input data among Architecture: Tightness level, roof, external wall, basement and window type, changing significantly the thermal transmittance (U), therefore the insulation level to the whole envelope. Moreover, a massive change was made on the energy supplies and air-conditioning system (HVAC).

5.1. Proposed retrofit solution

Following retrofit strategies, several solution were modelled for each type of building:

A. Lower insulation with a central AC

B. Higher insulation with central AC
C. Higher insulation with ductless AC
D. Lower insulation with ductless AC,
    1) Hot-water by electrical boiler
    2) Hot-water by heat-pump

A general increase of the insulation, which involved two levels of intensity, accompanied by the installation of carbon-free devices, which provide heating, cooling and hot water heating services.

5.1.1. Insulation

The insulation involves many reinforcement on the thermal transmittance, through the application of high-performance materials on every element of the building. The two levels differ from the type of material used, so from the U-value (thermal transmittance) obtained. One was designed for slightly colder climates (Aveiro) and the other for slightly warmer climates (Catania).

5.1.2. HVAC/supply system

Regarding the energy services, two main solutions are designed for the heating/cooling system. Among the several options illustrated in CEA Database and NZEB report, it has been chosen to focus VSA energy system on two main solutions: A Central AC (frequently involved in Passivhaus projects) and Ductless AC. First, the hybrid air/air heat pump, which provides, through a centralized duct system, both heating and cooling power to the whole building. Secondly, the ductless system is powered by a mini split air-conditioner, as air cooler, along with electric radiators for the heating; unlike the duct system, this solution requires one device for each room. Unlike the central AC, which use a mechanical economized ventilation, the ductless is modelled choosing a natural ventilation, exploiting the windy climate of the Country.

Finally, for the hot water heating, three different possibility are proposed; one involves the centralized heat pump, since the hybrid configuration is also designed for the HW. The ductless system has two possibility: an electric boiler or a water source heat pump. As mentioned above, every device consumes electricity, rather than fossil fuels. A photovoltaic-thermal panel system allows you to power every building in the district, making a big contribution to the energy supply.

6. Results

6.1. Comfort chart

For each new configuration, the thermal comfort plot shows great improvements compared to the current scenario, being most of the occupancy points shifted toward the thermal comfort zone (figures 8,9) The ductless solutions have gained a good growth of comfort, although humidity is a little too high for both seasons. The most effective comfort solutions are the central AC, the A and B, whose graph shows far fewer external points from the comfort zone. Generally, the higher insulation (B and C) presents better conditions for the moisture level. Nevertheless, refurbishing a moderate level of insulation, solution A, offers a good compromise; with great comfort improvement, it avoids not-necessary heavy insulation and cuts the energy demand.

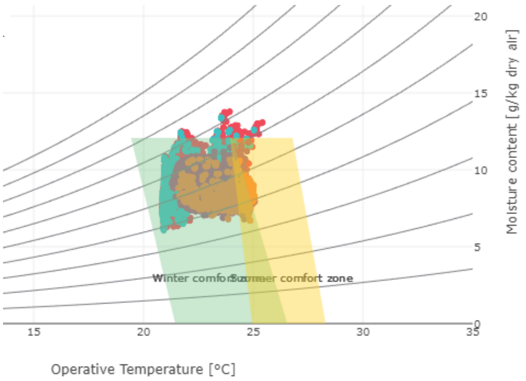


Figure 6. Comfort chart of the new VSA– (B) high insulation central AC

6.2. Energy – final use

Among the several outputs available, the energy demand calculation was focused on the final use, following the current scenario analysis. The high level of tightness carried by retrofitting together with higher efficiency HVAC, cut significantly the consumptions. The central AC package, thanks to the hybrid heat-pump high efficiency allows us to feed all the utilities with about 25 kWh/m^2×yr (B), a few more kWh if the insulation decreases (A). Especially, with higher insulation values, heating needs are less, while cooling increases a little more. The same situation happens with a ductless configuration. The ductless consumptions are quite higher if we see the case C and D1, due to the heating and hot water system. With the electric radiator instead of the heat pump the HW consumptions are three times more (from 5 to 15 kWh/m^2×yr), because of the lower efficiency. However, the cooling demand is smaller with the mini-split, 0,43 kWh/m^2×yr (C), rather than 1,64 kWh/m^2×yr of the ducted heat pump (B).

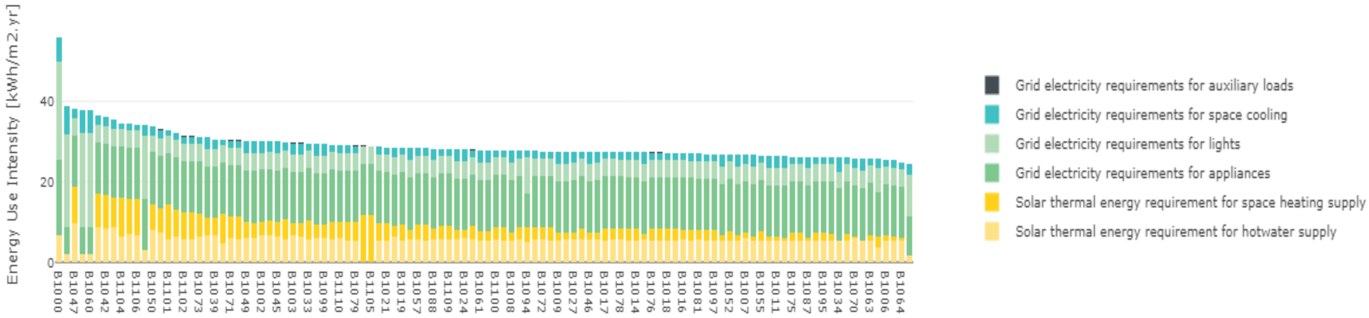


Figure 7. Energy final use intensity [kWh/m^2×yr] of the new VSA – (B) high insulation central AC

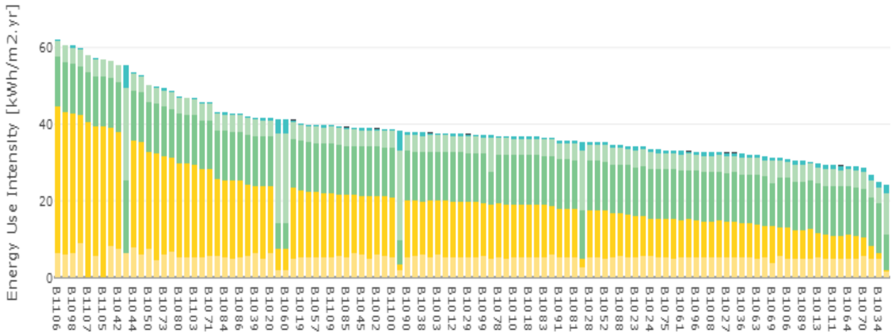


Figure 8. Energy final use intensity [kWh/m^2×yr] of the new VSA– (D2) low insulation ductless AC with solar heat pump hot water

6.3. Emissions

The tool LCA calculated for every solution an amount of emissions lower than the current scenario – a decrease from 600 kgCO$_2$eq/occ × yr to 200 kgCO$_2$eq/occ on average. Looking at the figure we see an average value of 10 kgCO$_2$eq/m^2× yr, 40% less than the current scenario.

Among the solutions, a small difference shows up for the embodied emissions, which are higher for the packages with a higher insulation. However, less insulation confirms a higher heating demand, so more emissions related to the energy system. The lowest emissions scenario possible happens when the insulation is moderately high and the supply system is very efficient, namely solution A. Higher insulations, allows to reach few degrees more during the winter but, on the other hand, they bring the investment cost and the CO2-eq emission to an increase.

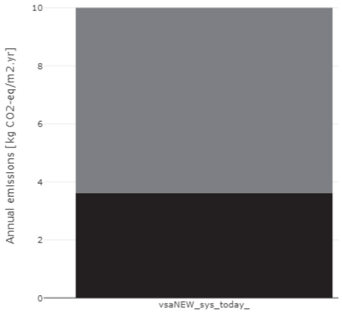


Figure 9. Annual emissions [kgCO$_2$eq/m^2×yr] of the new VSA normalized to net floor area - (A)

7. Discussion of the results

Both cases of insulation are successful in terms of comfort and in energy saving. Higher is the level of insulation set (mostly thanks to a lower transmittance, U), lower are the consumptions. Even though the CO2 emissions are slightly higher with the applications of more complex materials, a higher insulation (B, C) allows many benefits. The results may represent an interesting examples of how tackling the houses transmittance could be the key for finally fix the Portuguese comfort issue. The insulation reinforcement allows to keep the heating almost to zero, as the mild climate let us expect. So, considering these outputs as reliable, the nearly zero goal is obtained.

Looking the average district amount of the consumptions (fig.8; fig9), it reveals a significant improvement compared to the current VSA, with a reduction from 40% (D1) up to 70% (B) of kWh/m^2×yr. For reaching the highest energy saving, the central energy system is the best solution, which supported with the highest insulation almost leads to zero the heating and hot water needs. Even the comfort is totally centred in the wellness area. Some drawbacks, however, emerge taking account the retrofit operation, such as: the intrusiveness of a duct system and its relevant investment costs. Despite the analysis result is not properly highlighting this aspect, the actual amount of capital costs embodies this retrofit is strategy biggest problem. Without any investment's help these measures could be rejected, although the such proved benefits. Moreover, at the retrofit level, the impact of a central plant could be not supported by most of the user, compared to a small gas condensing boiler, cheaper and less intrusive. Nevertheless, a good compromise is proposed with the mini-split solution, which keep an acceptable level of comfort and consumptions, cutting up to 60% the consumption with the heat water heating heat pump, and 50% without the heat pump, but with the highest level of insulation. Probably, a better result could be obtained allowing to use the minis-pit as well as for the heating, since the electrical radiators sin of a low efficiency. This is globally a better solution terms of costs and intrusiveness, maybe more affordable for the Lisbon average customers.

The emission results (10 kgCO$_2$eq/m^2×yr) are a significant cut but not enough for reaching the net zero target by 2050. However, in CEA, some inaccuracy occurs in this field; for instance, how could be the grid electricity meant by CEA. It may involve an excess of emissions per kWh produced, being Portugal's grid powered by a huge number of renewable sources.

Although the CEA simulation is not totally representative, it confirms which measures may represent the path to take for not depending on the fossil fuel anymore, using renewable source for cutting as more as possible the CO2 emission and for decreasing massively the operating costs.

8. Conclusion and future outlooks

Portugal's fundamental step for cutting more than 95% GHG emissions by 2050 must occur impacting the buildings. The UBEM is helpful to attempt this goal, going toward the building self-sufficiency request. CEA, meeting the expectations of the literature, demonstrated to be a suitable tool for planning at the district scale. The best performance of the tool needs, however, a great amount of data, which not always have been available. Despite using the data available (from ADENE, INE), many inputs had to be invented and approximated. The results are so, not totally reliable due to the lack of accuracy. Another source of inaccuracy occurs for the scale adaptation, since the measures were applied massively to the whole district. Hence some choices might not be as detailed as they may have been planning for each singular building.

Nevertheless, they showed a good level of coherence, comparing the VSA plots with the actual Portuguese energy demand and emissions. Proceeding with the district optimization, trusting the results, we can purely realize that a proper envelopes and windows refurbishment would eliminate massively the thermal comfort lacks. The best retrofitting solution obtained involves a centralized AC system with an air heat pump, powered by a photovoltaic-thermal system. With 25 kWh/m^2×yr, the simulated energy demand is fully matching the standards of a Nearly-zero building. Furthermore, as shown in Figures 10 and 11, one-third of the demand is fed by solar resources. Despite the fluctuation of the solar and wind power, through the huge amount of electricity produced by Portugal, the country's electrical grid could power this range of residential demand, cutting significantly the emissions.

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