UNIVERSITY OF ZAGREB

FACULTY OF CHEMICAL ENGINEERING AND TECHNOLOGY

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SUSTAINABILITY STUDY OF AN ENERGY EFFICIENT HOUSE

MASTER THESIS

UNIVERSITY OF ZAGREB
FACULTY OF CHEMICAL ENGINEERING AND TECHNOLOGY

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He handed in him diploma thesis of the day: 16 June 2023

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ABSTRACT

Azalea UPV is a project formed in 2017 in the Polytechnic University of Valencia which aims to revolutionise our way of living through sustainable building methods that make buildings and cities more environmentally friendly. These objectives are part of the Solar Decathlon Europe competition, an international contest in which European universities are challenged to design and build prototypes of modular, sustainable, and highly efficient solar-powered houses.

The Solar Decathlon competition consists of ten contests in which the teams from the different universities are reviewed. These contests include topics such as architecture, engineering, energy efficiency and sustainability.

The design of the prototype started in 2019 with the aim to participate in the Solar Decathlon Europe in Wuppertal, Germany, in 2022. The project intends to develop a sustainable, innovative and energy efficient house which still maintains Valencian buildings traditional aspects.

To achieve these objectives, the members of the team designed the whole house, from the structure and the interior design to the water, heating, ventilation, and energy installations. Then, when the prototype was already designed, the team built it in Valencia, dismantled it and built it again in Wuppertal for the competition.

The project's most important outcome was the development of sustainable and efficient solutions that respect the cities traditions and that could and should be implemented in traditional building, as it is one of the activities that contributes the most to climate change.

In the Azalea project, I was the sustainability manager and personally responsible for the LCA, and the carbon footprint and loop potential calculations. I was also involved in the selection of materials and the development of systems and measures to reduce energy demand and consumption, and therefore environmental impact. In this last task, I worked with colleagues from the architecture and engineering departments of the project.

The aim of this thesis is to analyse and explain the work done for the prototype to be as sustainable as possible. This includes various aspects as the selection of materials, the analysis of the prototype's energy performance, the development of passive measures which reduce energy consumption, the design of photovoltaic and solar thermal systems to power the house

with its own energy, and the Life Cycle Assessment of the house, which includes the calculation of its carbon footprint.

ACKNOWLEDGEMENT

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I would also like to thank my Azalea UPV project colleagues for the work we did together when designing and constructing our house. They did an enormous job and none of the subjects treated in this thesis would have been possible without them.

Finally, I am thankful for my family and friends who have supported me while I was working on the thesis.

CONTENTS

1. INTRODUCTION

1.1. GENERAL OBJECTIVES OF THE THESIS

This thesis is an academic work, so one of the main objectives is the demonstration of the knowledge acquired throughout the degree and the extension of the same.

The work is based on the sustainability study and the carbon footprint calculation of an energy efficient house. This house was designed and constructed by the Azalea UPV team for the participation on the Solar Decathlon Europe 2021-22, a European competition which challenges university teams to build solar powered, energy-efficient and sustainable houses to compete in contests such as Architecture, Engineering or Sustainability.

The final objectives of the thesis are:

On the one hand, to carry out a Life Cycle Assessment of a house that is designed and built in a sustainable manner, in order to highlight the difference that this kind of construction can achieve in the building sector. The calculation is carried out with different softwares such as UMI (Urban Mining Index) and also using documents from manufacturers which detail the impact of their products.

On the other hand, to analyse the measures taken in the project that contribute to reducing the carbon footprint and the energy consumption, and therefore the construction's impact in climate change. In order to do this, first an energy study of the house and its situation is carried out to determine the most effective measures to be taken. These measures include passive ones, which reduce the energy demand and active measures that reduce the energy consumption.

With these two points achieved, a path to sustainability in construction is meant to be defined.

1.2. STATE OF THE ART OF SUSTAINABILITY IN CONSTRUCTION

Traditional construction is based on a linear economic model, which consists of the extraction of resources, the production and use of goods and services, and their disposal, generating a large consumption of energy, non-renewable resources and a large amount of waste, causing, in turn, wear and the loss of biodiversity.

There are three main problematic aspects in construction that contribute to contamination and climate change: resource consumption, waste generation and energy consumption.

“The construction and use of building in the EU account for about 50% of all our extracted resource and energy consumption, as well as about a third of our water consumption.” (European Commission, 2014).

Nowadays in the European Union, buildings are responsible for 40% of the energy consumption and 36% of the greenhouse gas emissions. This comes mainly from construction, usage, renovation and demolition.

The United Nations Sustainable Development Goals (SDGs) call for a change in the building sector, as they do in many others. The SDGs which are most related to the sector are:

- **Goal 11. Make cities and human settlements inclusive, safe, resilient and sustainable**: this includes aspects as sustainable urbanization (11.3) and reduction of the adverse impact of cities (11.6)
- **Goal 12. Ensure sustainable consumption and production patterns**: including sustainable management and efficient use of natural resources (12.2), achievement of the environmentally sound management of all wastes throughout their life cycle (12.4) and substantially reduce waste generation through reduction, recycling and reuse (12.5).
- **Goal 13. Take urgent action to combat climate change and its impacts.**

However, the data shows that progress regarding most of these goals is not fast enough as it should be to achieve them, as it is shown, for example, in the “Progress towards the Sustainable Development Goals: Towards a Rescue Plan for People and Planet”, a document issued by the United Nations which provides information on the progress made towards achieving the SDGs. The following are some of the comments made on the document on the SDGs mentioned above:

- Goal 11:

The world is far from achieving the goal of sustainable cities (…) To achieve SDG 11, efforts must focus on strengthening capacities for planning for urban development, improving access to public transportation and enhancing waste management. (United Nations Secretary General, 2023, pp. 17-18)

In 2022, the global average municipal solid waste (MSW) collection rate in cities was at 82%, and the average MSW managed in controlled facilities in cities was 55%. Uncollected waste is the source of plastic pollution, GHG emissions, and sources of incubation for infections. (United Nations Secretary General, 2023, p. 18)

- Goal 12:

The global economy also needs to speed up the decoupling of economic growth from resource use by maximizing the socio-economic benefits of resources while minimizing their negative impacts. (…) To deliver SDG12, it is crucial to implement policies that support the shift to sustainable practices and decouple economic growth from resource use. (United Nations Secretary General, 2023, p. 18)

- Goal 13:

The world is on the brink of a climate catastrophe and current actions and plans to address the crisis are insufficient. Without transformative action starting now and within this decade to reduce greenhouse gas emissions deeply and rapidly in all sectors, the 1.5°C target will be at risk and with it the lives of more than 3 billion people. (United Nations Secretary General, 2023, p. 19)

Global temperatures have already hit 1.1°C, rising due to increasing global greenhouse gas emissions, which reached record highs in 2021. Real-time data from 2022 show emissions continuing an upward trajectory. Instead of decreasing emissions as required by the target to limit warming, carbon dioxide levels increased from 2020 to 2021 at a rate higher than the average annual growth rate of the last decade and is already 149% higher than pre-industrial levels. Projected cumulative future CO2 emissions over the lifetime of existing and currently planned fossil fuel infrastructure exceed the total cumulative net CO2 emissions in pathways that limit warming to 1.5°C (>50%) with no or limited overshoot. (United Nations Secretary General, 2023, p. 20)

1.3. URBAN MINING AND LIFE-CYCLE ASSESSMENT.

1.3.1. Urban Mining

Our current model of economics and production is a linear model in which materials are extracted from their natural cycles, made into products (or buildings) and finally disposed after their use. This causes scarcity of materials such as sand, copper or zinc, which will soon enough be unviable to extract from natural sources.

In order to prevent this, there needs to be a transition to a circular economic and construction model, with responsible production and consumption of natural resources. To minimise the construction impact, it must be borne in mind all phases of material production, on-site construction, use and maintenance of the property and, finally, the dismantling of the building. It is also important to ensure durability and maintenance in order to avoid demolition.

When building a new construction, there is now a need to think about the dismantling phase to be able to reuse materials at the end of the building's life.

The concept of Urban Mining refers to the process in which the city, and therefore buildings, are understood as warehouses from which to obtain materials for new constructions, turning the city into a source of resources through the recovery and reuse of products.

With this new way of thinking about existing constructions, it is important to ensure that it is as simple as possible to obtain and reuse or recycle products and materials from buildings. Here is where modular construction and dry assembly methods are key. Dry construction allows easy assembly and disassembly of elements, and modules can even be reused as a whole or with minor modifications in different projects.

1.3.2. Urban Mining Index

The Urban Mining Index (UMI) is a tool developed by Dr. Anja Rosen in 2020 which intends to give a quantitative view of Urban Mining. It is a quantitative assessment of the recycling potential of buildings.

Over the entire life of the building, all the introduced materials and the resulting and waste materials are evaluated according to the quality they retain and the future use they can be put to. The ease of disassembly is also considered, as products or materials which are difficult or expensive to retire from a building being dismantled will probably not be recover.

The UMI software provides two percentages: the Closed-Loop Potential and the Loop Potential.

The closed-loop potential is the percentage of materials and building materials of a construction that can be kept in closed cycles without loss of quality.

The loop potential of a construction includes not only the percentage of closed-loop materials but also the percentage of materials and building materials whose quality diminishes in open cycles under consideration of defined criteria (further use and downcycling). The loop potential thus maps open loops in addition to the closed loops.

By combining both closed-loop and loop potential the Urban Mining Indicator is obtained. This indicator is the weighted scale at building level. In order to reflect the quality loss of materials kept in open cycles, only half of their share is included in the Urban Mining Indicator. Then, the pre-use and post-use phases are combined into an overall score.

The Urban Mining Indicator is the fastest way of comparing the recyclability or reusability potential of different constructions.

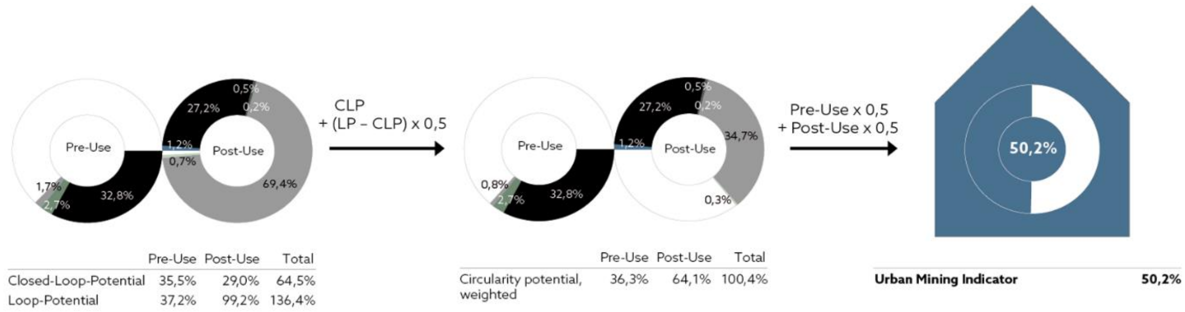

Figure 1. Urban Mining Indicator

The UMI software also provides the carbon footprint calculation of the materials introduced in it, therefore it is the main tool utilized for this purpose in the thesis.

1.3.3. Modular Construction.

Modular construction, also known as off-site construction, is a construction method that consists of the factory pre-fabrication of modules that are later assembled on site to form the final building.

Some of the advantages modular construction offers are:

- **Quality of work**: by working in a protected and more comfortable environment rather than on-site, the quality of work improves substantially, resulting in less mistakes that involve fixing or repairing in the finished building.
- **Loop potential**: modular construction often includes dry assembly methods which make assembly and disassembly easier and do not damage the products and materials being dismantled, improving the chances of them being recovered for future constructions.
- **Construction times:** apart from improving the quality of the construction itself, working in weather-protected factories reduces overall construction times, as processes take place regardless of the weather conditions. The on-site construction time is also reduced, as the only on-site activity is the assembly of the modules.
- **Cost reduction:** a module design can be used in different buildings, resulting in not only a reduction of the design cost, but also in a greatly improved possibility that the module can be reused in the future.
- **Construction waste:** by improving the quality of construction and increasing the loop potential of buildings, a reduction in construction waste is achieved.
- **Durability:** apart from the increased durability coming from the quality improvement, modular construction facilitates the exchange of parts of the building when necessary, therefore prolonging its life.
- **Flexibility and scalability:** modular construction is easily scalable by increasing or decreasing the number of modules being used. It also offers the option of reconfiguring a space by changing the modules position.

1.3.4. Life-Cycle Assessment

The Life-Cycle Assessment is an internationally recognized tool which provides an objective and rigorous identification of the environmental impacts of a technology or product during the all the phases of its life cycle, from the instant in which its development is started to the instant in which it disappears.

The LCA is a useful tool for improving the environmental performance of a product, as it analyses the performance in different points of its life cycle.

A LCA consists of four stages (ISO 14040):

- Goal and scope definition: the system boundaries and the level of detail is determined here, as not all LCA require the same level of precision and the importance of the different LCA phases differ from one product to another.
- Life Cycle inventory analysis: an analysis of the input and output flows of materials and energy in all the stages of the product's life cycle.
- Life Cycle impact assessment: the environmental and human health impact of the resources being utilised is evaluated.
- Life Cycle interpretation: the previous phases results are analysed. With the conclusions drawn from this interpretation, measures which improve the stages with the most environmental impact can be proposed.

It must be noted that LCA results indicate potential impacts which do not predict actual environmental effects. Even though, it is still a great tool to reduce impacts, as it can be used to improve future products or processes by identifying its most harmful stages or components.

In the next figure the different stages of a LCA according to EN 15978 are shown. The stages marked in red are the ones being considered in this thesis.

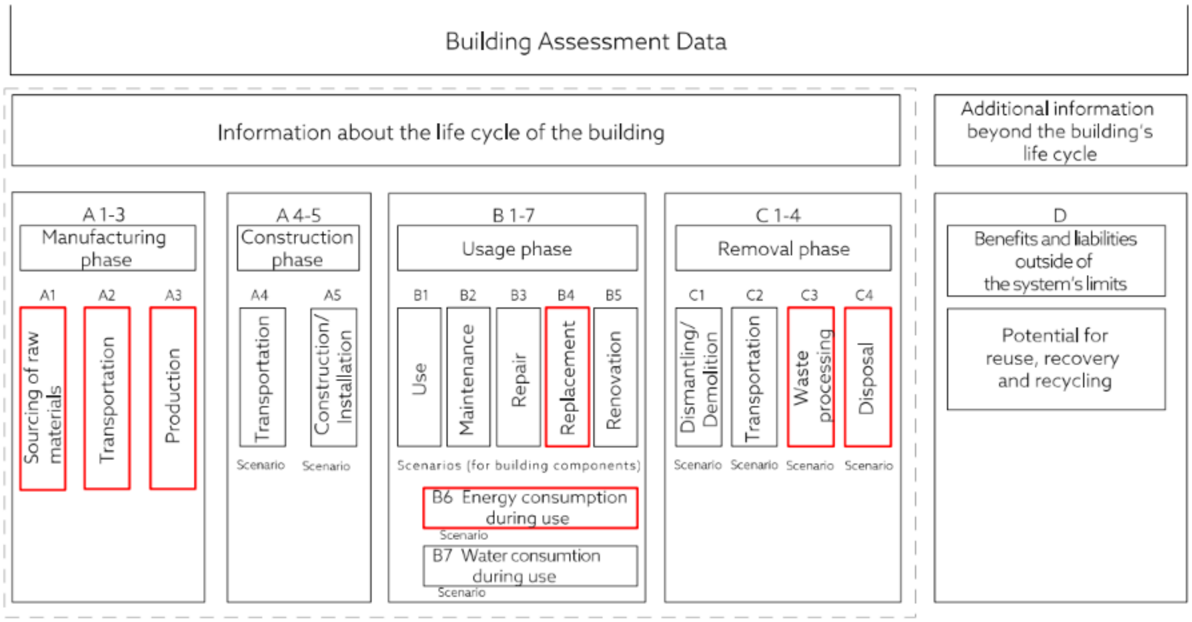

Figure 2. Components of a LCA according to EN 15978.

Module D "Benefits and liabilities outside of the system's limits" is also calculated, as it is one of the results obtained from the UMI software. Module D values the materials and products potential benefits beyond a building's primary use.

When using Module D in a carbon footprint calculation, the impact is positive, as the recycling or reusing potential of materials is interpreted as negative carbon footprint.

This is the reason why module D is not always included. Even though it is important to value the potential of these materials, the "negative carbon footprint" is not real. It needs to be considered that if a material with potential to be reused is finally utilized in another building, it will reduce the carbon footprint of the second construction, as it is probably replacing a new manufactured product. Therefore, using module D is useful when analysing a single building, as it is the case in this thesis, but when analysing a building and its "successor", using module D may result in falsely doubling the benefit of reusing.

1.3.5. Carbon footprint.

The carbon footprint is the total amount of greenhouse gas emissions associated with an individual, an organization, an activity or a product.

It is expressed in terms of carbon dioxide equivalent (CO_2e). This unit is used to express the Global Warming Potential (GWP) of a certain greenhouse gas in relation to CO_2. By using this unit is easier to compare different carbon footprints, as it provides a single measurement so that there is no need to compare gas by gas.

For example, 1 kg of nitrous oxide equals 298 kg of CO_2e. This means that nitrous oxide contributes to GWP 298 times more than CO_2.

1.3.6. Environmental Product Declaration

ISO 14025 defines Environmental Product Declaration (EPD) as a declaration that "quantifies environmental information on the life cycle of a product to enable comparisons between products fulfilling the same function". The EPD is based on a LCA made for the product, and in cases as the one analysed in this thesis, the data that provides is used to carry out the LCA of the bigger project that includes the product.

1.4. AZALEA UPV AND SOLAR DECATHLON EUROPE.

This thesis analyses the performance and measures taken in a house constructed with the objective of participating in the Solar Decathlon Europe competition.

The competition asks the different teams to develop a house that is suitable for both the team's city (Valencia, Spain in this case) and the competition's site (Wuppertal, Germany).

House Demostration Unit: the House Demostration Unit (HDU) is the prototype the team designs and builds.

Figure 3. Azalea UPV HDU

Escalà: The escalà is incorporated into the project as the main character of the proposal. Located on the north party wall, it acts as a thermal cushion to improve the building's energy performance.

2. EXPERIMENTAL PART

In this chapter, an analysis of the specific measures taken in the development of the project is carried out. This includes the analysis of the aspects that affect the energy performance of the building, as well as an explanation of the measures taken to reduce both the energy demand and the energy consumption.

Apart from this, the LCA of the building is also developed.

2.1. ENERGY ANALYSIS.

2.1.1. Climate analysis.

As the building is designed for the city of Wuppertal, in Germany, a climate analysis of the area needs to be carried out to determine the energy needs of the house.

Wuppertal is located in the Koppen Cfb area, which is characterised by cold winters and mild summers. The average temperature of the city is 10.5 °C, with the average temperature of the coldest month being around 2 °C and never reaching the monthly average temperature of 20 °C. The average winds are breezes of 4 m/s of southern component and that barely exceed 14 m/s occasionally. The average annual radiation of the area is 942 kWh/m^2.

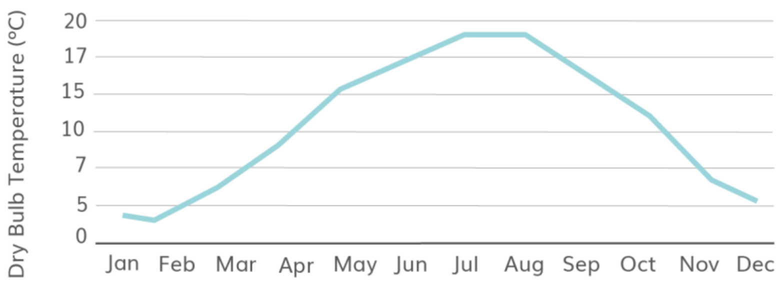

Figure 4. Wuppertal temperature.

Rainfall is evenly distributed around the year, with the driest periods being Spring and Summer.

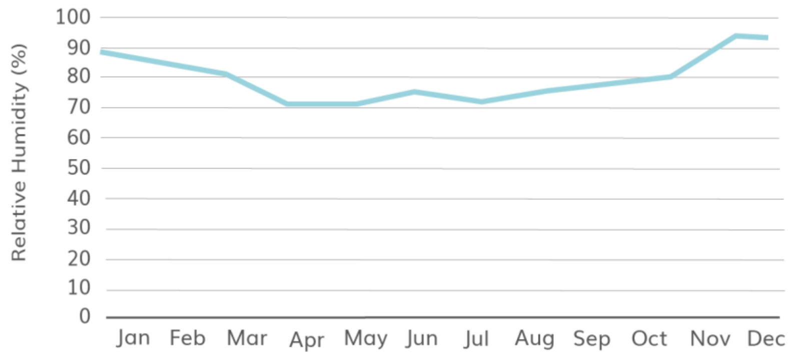

Figure 5.Wuppertal humidity

The average winds are breezes of 4 m/s of southern component and that barely exceed 14 m/s occasionally. The average annual radiation of the area is 942 kWh/m^2.

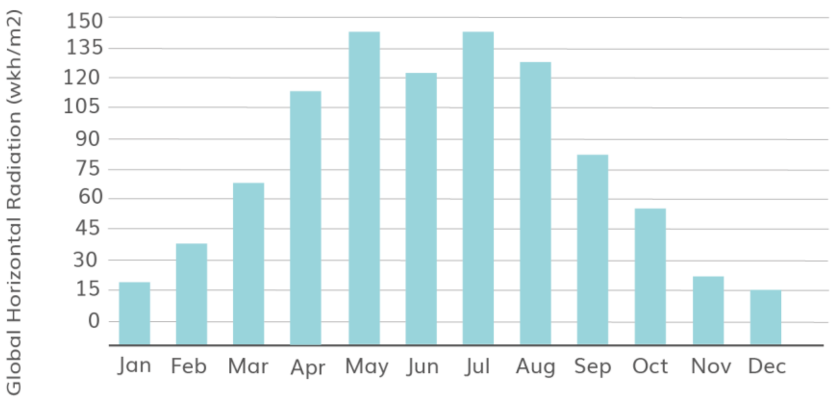

Figure 6.Wuppertal radiation

2.1.2. Passive measures for demand reduction.

Envelope: For the HDU two different insulation technologies are chosen: recycled cotton for the main part, and rice straw for the escalà and the machine room. Both materials have low thermal conductivity, enough to achieve a wall transmittance of 0.18 W/m^{2}K.

Recycled cotton has been used as an insulating material in the modules that cover the fitted-out area of the house. This is a reused material that comes from the recycling and regeneration of clothing scraps from the textile industry. The name of the supplier company is RMT Insulation, and the product is NITA-COTTON.

This insulation has a high thermal and acoustic insulation capacity, is durable, breathable and free of toxic agents and it has been introduced in the modules with a density of 30 kg/m3.

In the modules that form the escalà and the machine room, rice straw has been chosen as the insulating material. This material comes from the vegetable remains obtained after harvesting rice. It is a natural, innovative, ecological and local insulator.

In the Albufera of Valencia there are large areas of land for rice cultivation. Every year, between July and September, the rice is harvested. In this process, apart from the cereal, rice straw is obtained, which is the plant remains of the plant itself that are not used as food. Traditionally, in order to eliminate this residue from the fields, farmers carry out controlled burns between October and December. This burning produces large quantities of CO2, which is a local pollution problem in the municipalities near the Albufera, including the city of Valencia. This insulation made of rice straw makes it possible to reuse agricultural waste for construction purposes, preventing it from being burnt and wasted.

The straw was subjected to a natural air-drying process in which its relative humidity was reduced to below 15%. Finally, the dried straw was introduced into the escalà and machine room modules with a density of approximately 80 kg/m3.

Figure 7. Cotton insulation.

Figure 8. Rice straw insulation

Escalà: The main function of the escalà is to increase the light and to form a double skin to improve insulation. This part of the house contains a large mass of air that acts as a thermal cushion, making the conditioned area less affected by high or low temperatures.

Natural ventilation: The natural ventilation system works thanks to the Caloret System, which will be used for the conditioned spaces when required, especially on hotter days.

The Caloret System is a device developed by Azalea UPV whose main function is to take advantage of solar radiation during the day to heat the air that will be used to ventilate the house in a nearly passive way, as only a fan is needed to drive the hot air into the house. In addition, when it is not required as a heating system, it also acts as a solar chimney, taking advantage of the accumulated heat to extract air from the house without the need for active ventilation.

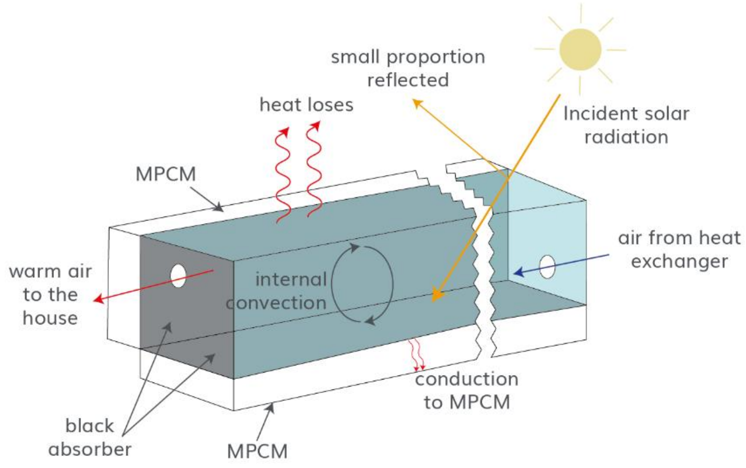

Figure 9. Caloret System

To complement this system, east and west windows are placed facing each other. The HDU is oriented to take advantage of the prevailing wind in Wuppertal, whose direction is SW-NE.

Solar tubes: The HDU is equipped with solar tubes to improve the lighting conditions in the bathroom. The sunlight is captured by a dome placed just above and transported by a highly reflective conduit. In this way, natural light is used instead of artificial light, reducing the lighting demand.

Shading: Wooden rolling blinds will be placed to prevent the passage of solar radiation at the desired times of the day but allow ventilation and the entry of diffuse radiation.

Orientation and window sizes: Some members of the team conducted an parametric analysis to determine the optimal orientation of the house and the widow to wall ratio that would provide the best energy results, with the results of this analysis being a window to wall ratio of 40%. The best orientation is with the two main facades with more openings to be at East and West.

2.1.3. Active measures for consumption reduction

HVAC: There is an air-water aerothermal system for generation and a fan coil system for distribution which use automatic flush fittings that open and close when necessary, prioritising DHW. Two expansion tanks have been implemented for each hot water stream of both circuits.

There is a glycol content of 40% in each 19-litre expansion tank based on the minimum temperature in Wuppertal, so that it is sufficient to overcome the maximum pressures.

The air-water heat pump is used both for heating and also for domestic hot water (DHW) when the solar system is not able to provide the whole DHW demand.

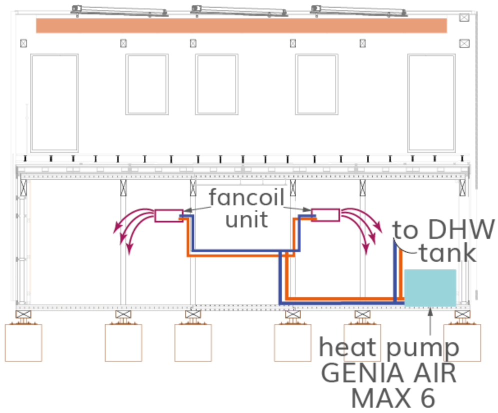

Figure 10. HVAC system

Solar thermal system: Due to the great performance of the vacuum tube panels in unfavourable climate conditions such as those in Wuppertal, this technology is used in the HDU. The model used is the VIESSMANN VITOSOL 300-TM.

The panels are placed on top of the escalà horizontally. This is possible when using vacuum tube panels, as they allow the interior of the tubes to be oriented. To cover the maximum annual demand, the inside part of the tubes will be placed at 25º, as this is the highest degree of inclination allowed by the tubes.

The domestic hot water (DHW) demand is calculated according to Spanish regulations, (28 litres/person/day for private residential buildings). This means that the demand is 84 litres/day.

In Figure 11 the solar fraction covered monthly and annually by the solar thermal system is shown. The solar fraction is the percentage of the demand covered by the system.

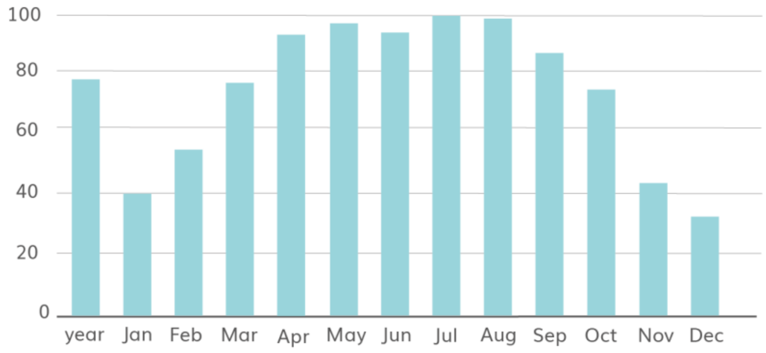

Figure 11. Solar fraction covered

The rest of the demand is covered by aerothermal energy. The deposit has three different coils, two for heating and one for consumption: for the solar thermal primary circuit, the heat pump circuit and the DHW consumption circuit. An intelligent system will optimise the use of solar thermal energy minimising the use of aerothermal energy to produce DWH. The water inside the tank will be always above 60 ºC in order to ensure legionella protection.

The outdoor unit has a COP of 3.77. The annual electrical consumption for DHW is 106 kWhe. The monthly electrical consumption for DHW is shown in Figure 12. Electrical consumption for DHW production (Living Lab).

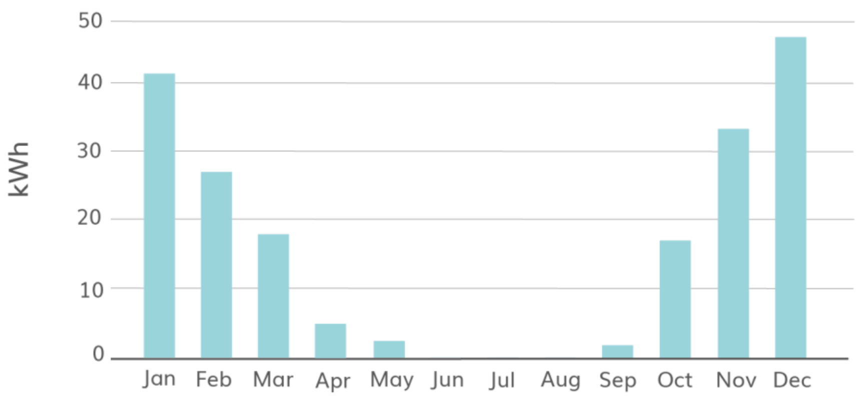

Figure 12. Electrical consumption for DHW production

Appliances influence: Appliances with low electricity consumption are selected. A “basic” oven is preferred, mechanically operated and with less cooking special features. That means that almost 2000 W of power peak is saved, which implies less heat losses and energy consumption per cycle.

The dishwasher was selected on the basis of some important features such as a short ECO cycle, being able to deactivate the heat drying option or having a minimum consumption of electricity and water. The same consumption saving rule applies to the TV choice.

In order to also reduce the carbon footprint, some of the appliances used by the team in previous competitions (SDE19) and that were also highly efficient were recovered and reused for the house. These include the washing machine, the tumble dryer and the freezer.

Filtering and water saving: The greywater treatment system collects water from showers and sinks and after a recycling process, it is used for irrigation, cleaning and toilet flushing.

A physico-chemical purification is carried out to ensure that it meets the necessary sanitary guarantees for its use.

In a first phase, a physical purification is performed through a filter that retains solids, such as hair or tissue remains. Subsequently, a chemical purification is made by adding a small dose of bleach or a product based on active oxygen to the water. This product is stored in a small compartment of the purifier and is applied automatically by means of a dosing pump, which operates for about three minutes a day.

Attached to this system is a 300 litres tank where the treated water and filtered rainwater goes. Rainwater will be reused for the same uses as treated greywater.

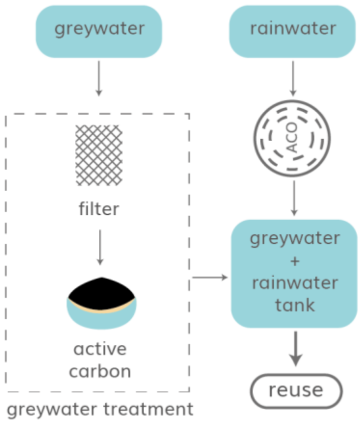

Figure 13. Water reuse scheme

Rainwater is collected from the surface of the courtyard through a pavement filtration system called Life Cersuds. Life Cersuds is based on the use of the permeable ceramic pavement shown in "Figure 14. Life CerSuds functioning". This permeable pavement is made from ceramic tiles of low commercial value which have been perforated, functioning as filtering systems. These tiles are used together with gravel boxes that have been placed underneath to complete the drainage. A 70 mm PVC drainage pipe is placed under the gravel, which collects the water and leads it to the tank.

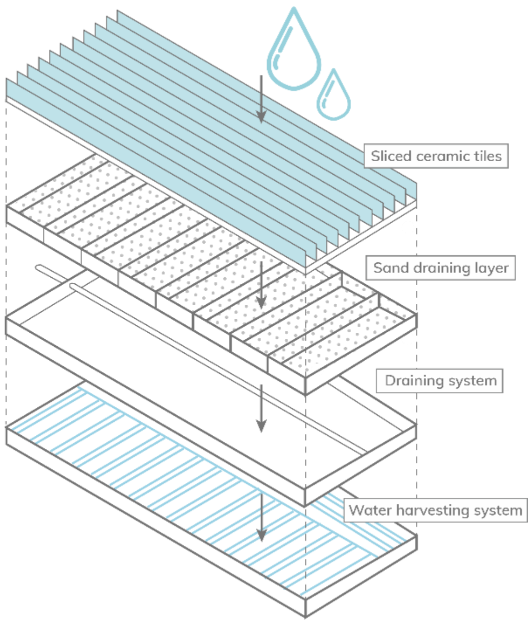

Figure 14. Life Cersuds functioning

To reduce the water and energy consumption the Smart Water system is used. It is installed at the end of the hydraulic supply circuit of the wet rooms. It incorporates a temperature sensor for hot water and a small recirculation pump. When the hot water tap is opened and the sensor detects that this water has not yet reached 35ºC (initial phase), the pump recirculates it through the cold water pipe back to the heater (intermediate phase). When 35ºC is reached, the valve is opened, the equipment gives an audible signal and water starts to flow out of the faucet (final phase). In this way, two simultaneous savings are obtained. It saves energy, since each time the water is recirculated to the heater, its temperature increases and the necessary heat transfer is lower. It also saves water, as otherwise the volume of water coming out of the tap would be lost until it is hot enough.

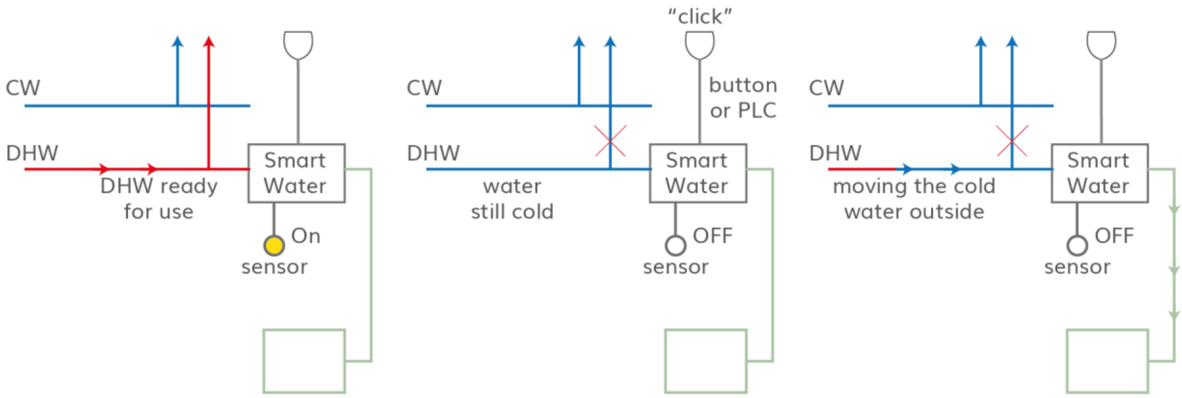

Figure 15.. Smart water initial, intermediate and final phases

The Passive Shower is also an energy saving system implemented in the house. The novelty of this shower is based on its tray. This includes an energy recuperator so that the hot water that falls into the tray and goes down the drain gives up part of its heat to the cold water that enters the shower, thus reducing the energy consumption of the house.

Apart from this, diffusers will be installed in all taps to reduce the water needed.

With all these measures, it is possible to achieve a reduction in annual water consumption of 10 m^3, almost 50% of the total consumption, as can be seen in "Figure 16. Annual water consumption HDU".

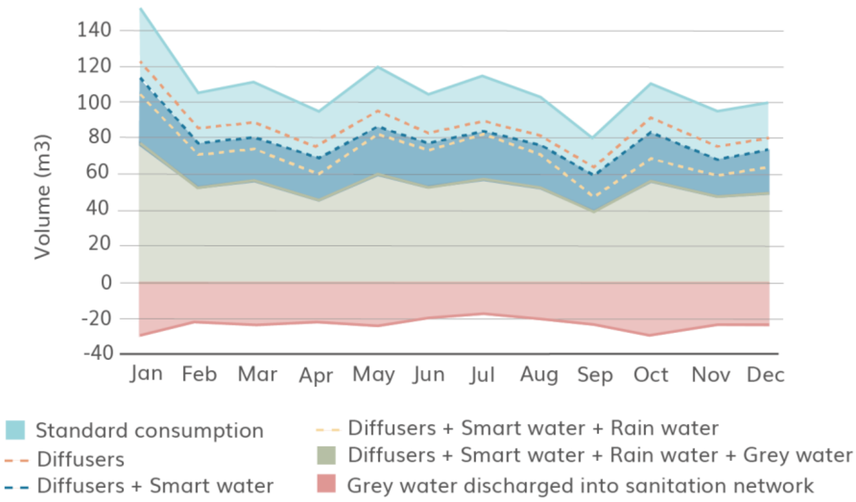

Figure 16. Annual water consumption

Final electricity consumption: After the implementation of the above electricity consumption reduction strategies, the annual electricity consumption of the HDU is 2086 kWh/year.

Energy supply: solar radiation will be considered as the primary energy source to supply the HDU, supported by the electricity grid.

The generating part of the photovoltaic installation is determined by the elements detailed in "Chart XX. PV generators".

Brand	Type	Efficiency	Units	Total power	Inclination
SunPower	Monocrystaline PV 375Wp	19,10%	4	1.500kWp	Variable
Onyx	Monocrystaline PV Glass 166Wp	11,70%	9	1.494kWp	Variable

Table 1. PV generators

To maximise the production during the whole year, a structure with variable inclination between 15º and 35º will be installed, with a limitation on 35º due to shadowing between the rows of panels. This seasonal variation of the tilt will improve the annual irradiation on the panels. A lithium ion 2,5 kWh battery is also implemented into the system.

2.2. LIFE CYCLE ASSESSMENT

This chapter discusses the measures taken to reduce the house carbon footprint (apart from the measures explained in the previous chapter which reduce energy consumption and therefore the carbon emissions), and the calculation of the carbon footprint itself.

The system boundaries for the LCA: The carbon footprint was calculated over a standardized life cycle of 50 years for the HDU with a reference area of 54,17 m^2.

2.2.1. Carbon footprint reduction

To minimise the construction impact, it must be borne in mind all phases of material production, on-site construction, use and maintenance of the construction and, finally, the dismantling of the building. It is also important to ensure durability and maintenance to avoid demolition.

During the design, the following measures are established to ensure the sustainability of the materials and the project itself:

- **The city is conceived as a source for obtaining and using materials.** Traditional ceramic pieces of Valencia and from current demolitions are reused for the interior finishes.
- **Reused materials and products from previous projects.** Leftover materials from the participation in the SDE19 are used, such as OSB boards, wooden pallets to make up the module of the HDU roof slab; or even the recovery of appliances.
- **Modularity and dry assembly.** As explained before, this boosts the products and materials recovery potential.
- **Use of wood.** The use of timber is one of the key aspects of sustainable construction. Wood is used in the envelope, the interior finishings and, most importantly, in the structure. Where concrete would be used in traditional construction, wood is used in the project. This is a really important measure, as wood has considerably less carbon footprint, grows naturally, is also a durable material and after multiple uses can be

composted. Wood used for the project comes from certified sustainably managed forests.

Materials: The choice of materials is made by means of a prior analysis, in which different aspects are considered: their layout and technical characteristics, studying their behaviour and durability; their life cycle, bearing in mind the raw material, together with the percentage of recycled product it contains and the possibility of being recycled and reused.

The structure of the building is developed with a system of laminated timber porticoes. The joints between these elements are made with metal parts. This allows their recovery and separation after the useful life of the building, as well as their reuse in other constructions.

The building envelope is mainly composed of wood-derived materials (OSB panels), straw and organic elements recovered from rice cultivation as insulation and recycled cellulose boards (Honext) as interior cladding.

The following figure displays the different materials used in the construction.

Material	Use/Function	Posible toxic substances	Content of recycled material	Circle load and future posibilities
Wood	Structure and substructure			
GL24H	- Beams and columns	Glues and Autoclave treatmen for exteriors elements		Wood can be recovered and reused. It can also be recycled, the main uses of which are: -Manufacture of chipboards -Energy recovery
CLT	- Slabs			
Wooden trips	- Substructure			
OSB	- Substructure enclosures	- Resines	Wood shavings	
Insulating				
NITA-COTTON	Thermal and acoustic insulation	Free of toxic agents and/or allergens	80% recycle fibers Regeneration of garment scraps	Can be recovered and reused. It can also be recycled into textile fabrics. Recycled product.
Rice straw	Thermal insulation		Rice cultivation waste	Can be recovered and reused for the same or other uses, such as cushion padding. It can also be used as compost and substrate for mushrooms. Recycled product.
Claddings/ pavements				
HONEXT	- Interior cladding		Recycled paper and cardboard	Can be recovered and reused or recycled while maintaining its quality, or paper, cardboard boxes or newspapers and magazines can be made from it. Recycled product.
Recycle plastic	Interior finishing and decoration	Plastic	Recycled plastic	Can be recovered and reused or recycled while maintaining its quality. Recycled product.
Micro T-64	False ceiling made of wooden acoustic panels for the passage of installations		From sustainable forests	Can be recovered an reused o recycled, can also be used for energetic recycling.
Ceramic	- Interior pavement Interior and exterior cladding		Ceramic pieces in stock or recovered from demolitions	The pieces can be recovered and reused. The ceramic can be crushed and recycled to make new ceramic pieces.

Figure 17. Self-consumption results

2.2.2. Tools and methodology for the carbon footprint calculation.

In this thesis only some aspects of a full Life Cycle Assessment are evaluated, as it is shown on "Figure 2. Components of a LCA according to EN 15978". The carbon footprint calculation is carried out in two different parts.

2.2.2.1. Construction elements footprint.

The construction elements footprint is calculated using the UMI software. All major construction elements are included, as the whole structure, the wood and insulation which conform the envelope, the interior and exterior claddings, doors and windows…

Other minor elements are not considered due to the negligible contribution they have on the carbon footprint.

The first thing needed when using the UMI is accurate measurements of every construction element considered. In this case, measurements were obtained from the project drawings.

Once the measurement of each material is done, the material mass is calculated with the product data sheet. This is necessary because the mass is the parameter introduced in the UMI.

The UMI separates the house elements in five categories: foundation, exterior walls, interior walls, roof and ceiling. The surface of each one of these categories has to be introduced, as then the mass of the different elements is entered per square meter.

All the data needed for each element is shown in "Figure 18. UMI inputs".

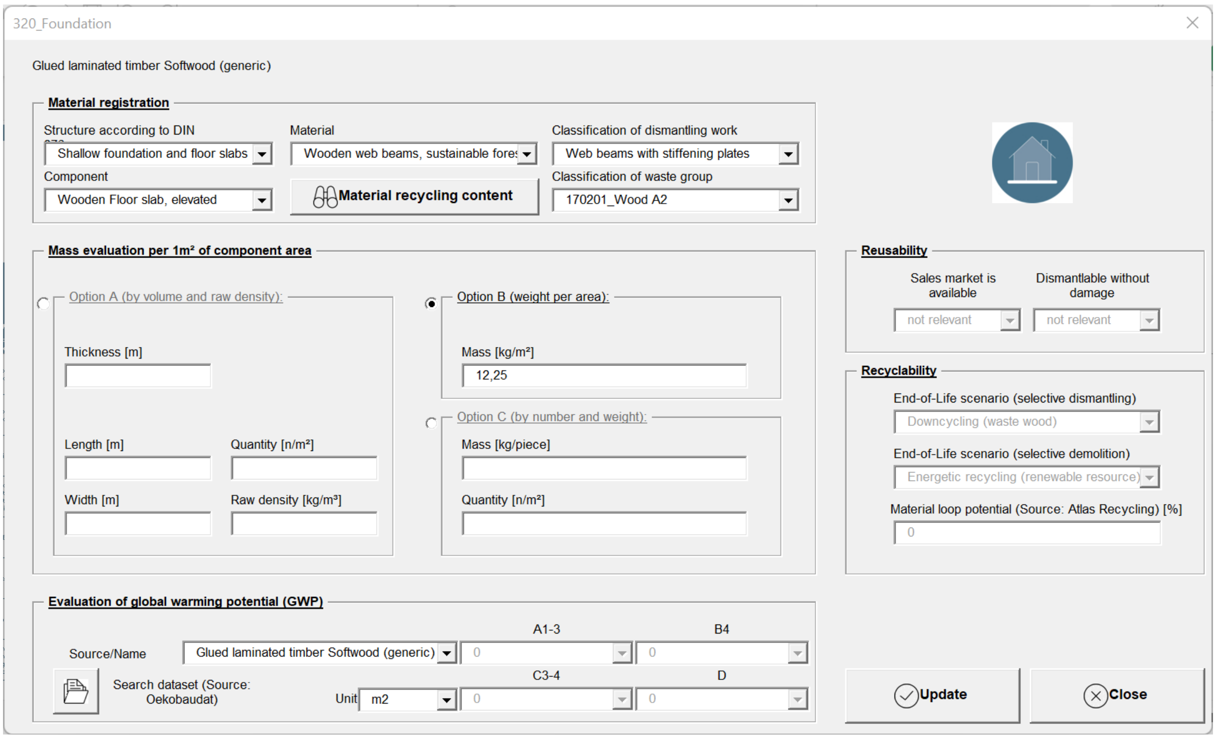

Figure 18. UMI inputs

In this window the type of material is introduced, as well as the mass per square meter and the possibilities of recyclability and reusability. When a product EPD was available, the data provided was entered into the "Evaluation of GWP" part. If the product did not have an EPD, the data was obtained from the UMI data base.

The "Material Recycling Content" is also introduced in the UMI.

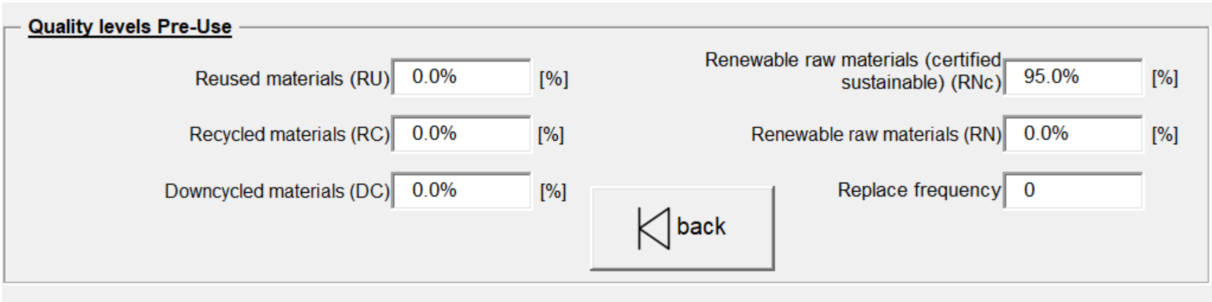

Figure 19. Material Recycling Content

When all the materials are already into the UMI, the results are shown as it follows:

In each one of the parts of the house the loop potential, closed-loop potential and global warming potential is shown, with the GWP being separated into four phases: production, replacement, disposal and benefits outside the system boundary.

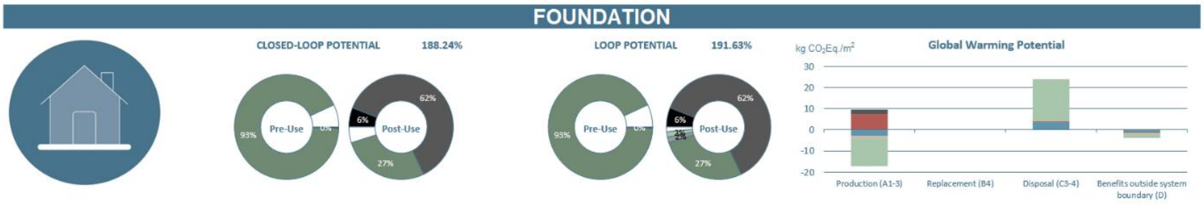

Figure 20. UMI foundation results

In the “results” tab, the overall loop potential, closed-loop potential and GWP of the house are displayed. Here the Urban Mining Indicator is also shown.

2.2.2.2. Technical elements footprint.

As the UMI software only allows the calculation of the construction elements, the products and materials which are part of the installations and other technical parts must be analysed in a different way.

To obtain the technical elements effect, three main aspects need to be considered:

- The manufacturing and removal phases impact was estimated using the products EPDs or the “Auxiliary table for LCA of building equipment” provided by the SDE when EPDs were not available.
- The impact generated by the energy consumption during the use is also considered. To calculate this impact, the kWh consumed are multiplied by a 0.2 kg CO_2eq/kWh factor. This factor is provided by the SDE organization.

  The feed-in electricity (electricity generated by the PV panels but not consumed and therefore fed to the grid) is considered as negative emissions. With the simulations carried out, the feed-in electricity is 1403.44 Kwh/year, which equals 280.69 kg CO_2eq/year.

- The replacement of some systems parts is also included by multiplying the GWP of the part replaced by the number of times the part is replaced in the period considered. The number of replacements was determined with harmonised tables provided by the SDE.

3. RESULTS

3.1. FINAL ENERGY BALANCE

The PV panels configuration leads to an annual energy production of 2648 kWh/year. Results of a self-consumption simulation can be consulted in "Figure 21. Self-consumption results".

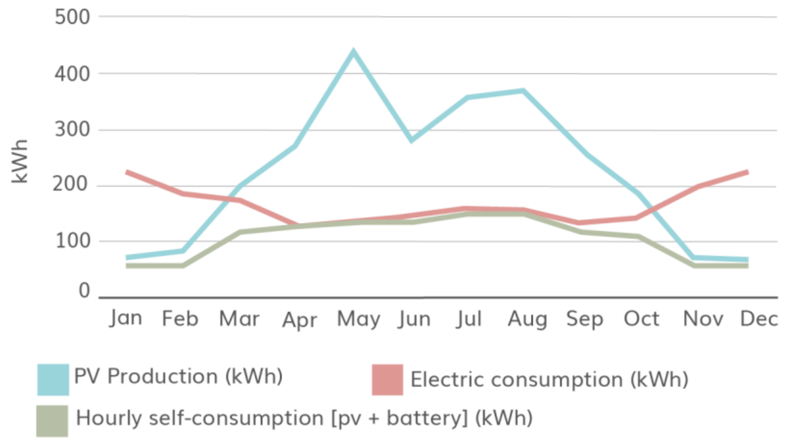

Figure 21. HDU self-consumption results

After all the passive and active measures to reduce both the energy demand and the energy consumption, the final energy balance between the production expected and the typical energy consumption is obtained. This balance divided monthly can be seen in "Figure 22. HDU annual energy balance".

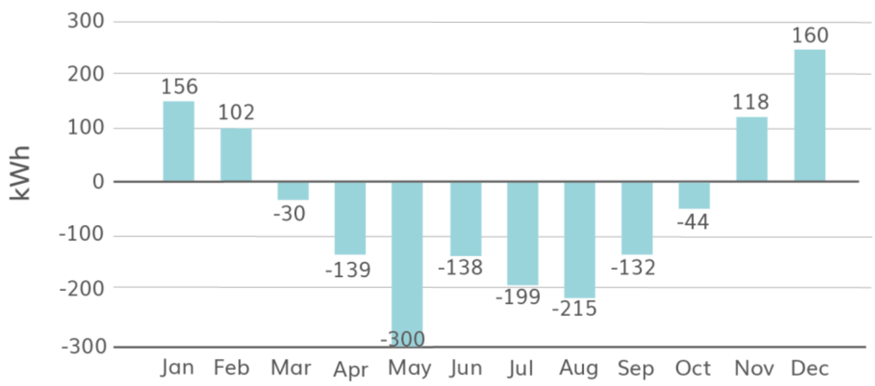

Figure 22. HDU annual energy balance

3.2. URBAN MINING INDEX RESULTS

The Urban Mining Index results are shown in "Figure 23. UMI loop and closed loop results". It shows both the loop potential and the closed-loop potential of the different parts of the house separated in pre-use and post-use.

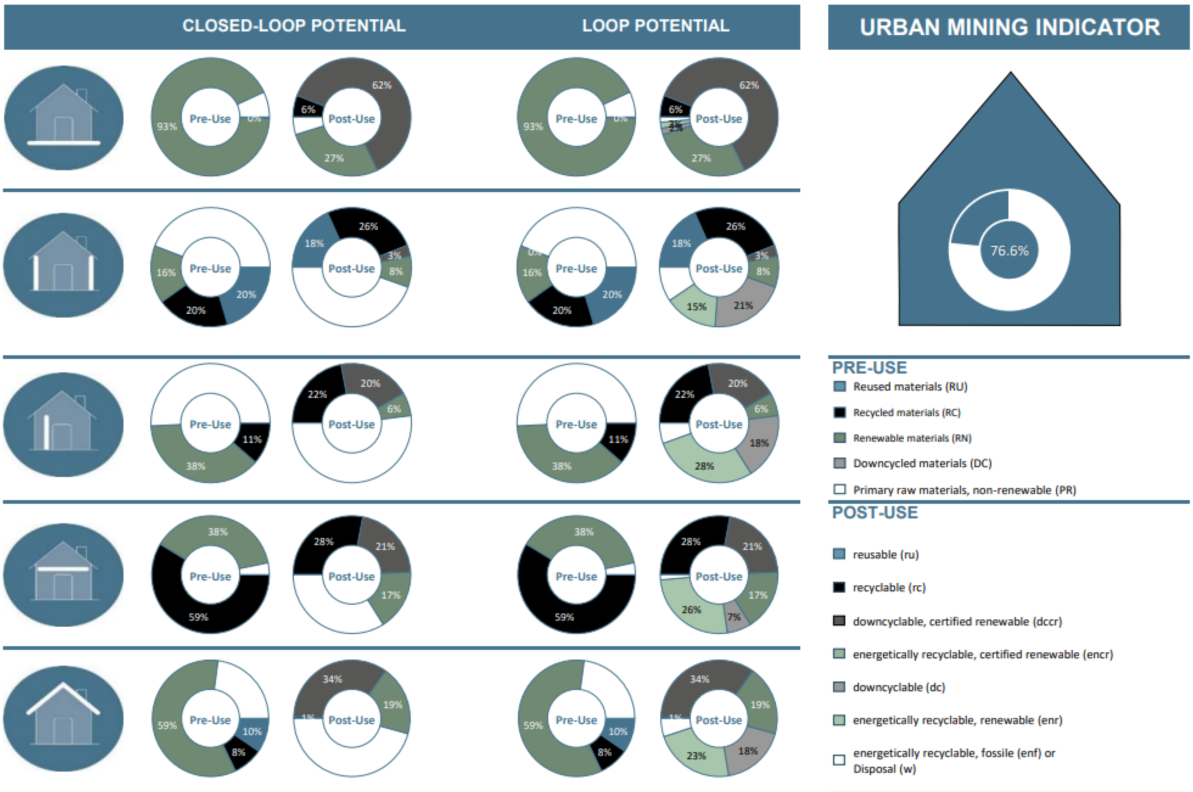

Figure 23. UMI loop and closed loop results

The Urban Mining Indicator is also shown in Figure 23. The HDU achieved an indicator of 76,6%.

3.3. CARBON FOOTPRINT RESULTS

3.3.1. Construction elements.

As explained before, the construction elements footprint is calculated with the UMI software. The results are shown in “Figure 24. Construction elements carbon footprint” separated in the different phases of the LCA and including phase D. It also shows the footprint of each one of the parts of the house and the footprint per square metre and year of life expected.

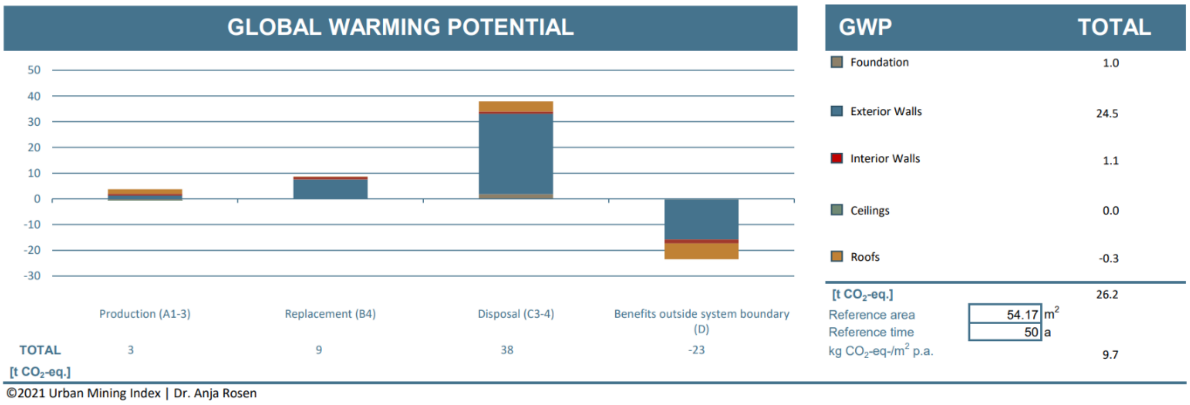

Figure 24. Construction elements carbon footprint

3.3.2. Technical elements.

The results obtained for phases A, B and C are shown in “Table 2. Technical elements phases A, B, C footprint”.

PART	Phase (kg CO2e)	Phase B (kg CO2e)	Phase C (kg CO2e)
ELECTRICAL INSTALLATION			
Cables	67.7	0	0
PHOTOVOLTAICS			
Module type 1	3714	3714	-
Module type 2	3699.1	3699.1	-
Battery (2,5 kW)	422.5	422.5	-
SOLAR COLLECTORS			
Excavated collector	421.3	421.3	-
Water tank	135.6	135.6	-
Pumping and installation	60.4	60.4	-
FLOW			
Greywater tank	22.6	22.6	-
Rainwater tank	135.6	135.6	-
Ducts total	91	0	-
SOLAR THERMAL			
Vacuum tube panel	776	1188.7	16.5
VENTILATION			
Ducts	1999.7	0	-
TOTAL	11454.5	9799.9	16.5

Table 2. Technical elements phases A, B, C footprint

For the energy consumption related emissions results are shown in “Table 3. Conversion of final energy consumption to CO2eq emissions”.

End use	Consumption (Kwh)/year	Tons of CO2	Kg of CO2
DHW	106	0.0212	21.2
Heating	1329	0.2658	265.8
Cooling	276	0.0552	55.2
Ventilation	406	0.0812	81.2
Usage related (without appliances)	423.5	0.0847	84.7
Other	64	0.0128	12.8
TOTAL	**2604.5**	**0.5209**	**520.9**
PV production	2648	0.5296	529.6
Own consumption	1244.56	0.249	248.912
Surplus	1403.44	0.281	280.688
Final electricity grid consumption	**1359.94**	**0.272**	**271.988**

Table 3. Conversion of final energy consumption to CO2eq emissions

3.3.3. Final carbon footprint.

Combining the construction and technical elements footprints the total footprint of the house is obtained. Phase D is not included.

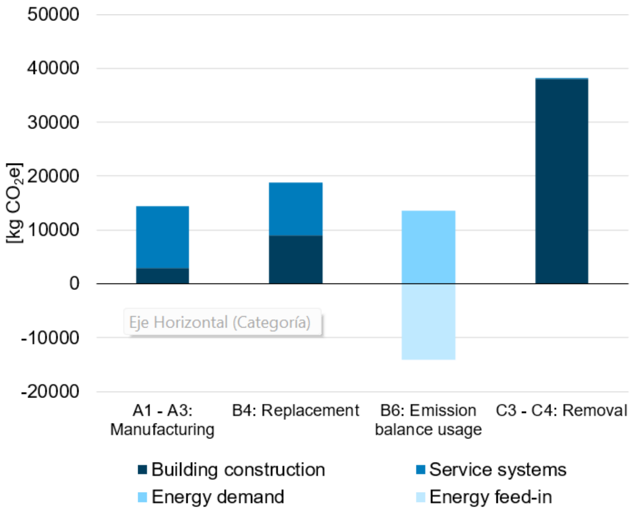

Figure 25. Final carbon footprint results

4. DISCUSSION

4.1. FINAL ENERGY BALANCE

Thanks to the low energy demand of the building and the high efficiency of the systems used, it is possible to generate more energy than the annual demand of the building.

As it is shown in “Figure 22. HDU annual energy balance”, in every month from March to October (both included) the energy balance is negative. This means that the energy production of the house via the photovoltaic panels is higher than the energy consumption of the house in that month and it is a success as it was one of the objectives of the project.

It may seem that the design should try to have an energy negative balance during every month, but it is necessary to keep in mind that this would mean a big increase in the amount of PV panels needed, which would not fit in the house, as well as in other parts of the PV system. It is also important to remark that, even if the possibility of increasing the number of panels existed, this has a cost in sustainability, as the production of panels has a non-negligible carbon footprint. Also, more panels do not necessarily mean that the energy production would be enough to compensate the consumption, as in the months in which the energy balance is positive with the actual configuration the weather conditions are not favourable.

The results regarding the house’s self-consumption are also satisfactory, as most of the energy produced is used by the house itself (see “Figure 17. HDU self-consumption results). When the energy production is bigger than the consumption part of the energy is used to charge the batteries of the system and the rest goes to the grid.

It is also interesting to compare the results of the energy balance in Wuppertal to the ones the house would have had in Valencia. Valencia has a Bsk Koppen climate classification, with warm summers and mild winters. The average temperature in Valencia is 16.8 °C, with the average temperature in the coldest month being 10.4 °C and in the warmest month 24.5 °C. The annual value of rainfall is 445 mm, most of them (190 mm) in September, October and November, with especially dry summer months. The received annual radiation is 1861.5 kWh/m^2.

This climate is very different from the one in Wuppertal, which has three times the amount of rainfall, half of the total radiation, and an average temperature six degrees lower than the one from Valencia. This means than the main needs in Valencia would be cooling rather than heating, with elements as the shading and the Caloret System (when used for hot air extraction) gaining importance to improve passive ventilation and the temperature inside the house.

The DHW electricity needs would also be smaller in Valencia, as the solar fraction with the three panels would be much higher thanks to the highest radiation. The supply water temperature would be higher also, reducing therefore the energy needed to heat it. In fact, if considering the construction of the house in Valencia or somewhere with a similar climate, a reduction of the number of both solar thermal and photovoltaic panels should be considered and new simulations would have to be carried on.

There is less difference when comparing the orientation and openings. The window to wall ratio in Valencia would be the same as in Wuppertal (40%). The orientation would also be with the biggest openings facing East and West. In Valencia, the results for this orientation stand out over the rest because the wind coming from the see has an East to West direction, which helps with the cooling needs, especially when considering areas near the seaside.

Systems which involve the reuse of rainwater would not be as effective as they are in Wuppertal in Valencia, as most of the rainfall in Valencia is concentrated in three months and when it rains it is normally very heavy rain. This means that in most months, very little water would be collected for reuse, and between September and December, the system would not be able to store all the rainfall. In Wuppertal, the rainfall is not only higher but also more evenly distributed through the year, which benefits these systems.

Some other aspects as the thickness of the walls and the insulation are equally as important in both cities (and it would be too in any other area), as a good insulation reduces the needs for both heating and cooling.

With regard to other aspects than the photovoltaic panels and their energy storage, other options are studied as alternatives after the project. For example, if there is a surplus of electricity produced, it could be used to produce hydrogen via electrolysis, which could then be converted back into electricity using a fuel cell. This is a great option in terms of sustainability, as it has zero emissions. The main problem is that the space required to store hydrogen is too large to fit on the house. However, the option of having a fuel cell in the house, with hydrogen delivered to the site to generate electricity, would theoretically be possible.

Regardless of this, photovoltaic panels with a battery are currently the best option, although as hydrogen is a newer technology, progress will certainly be made in this area. Finally, when using hydrogen, it is always important to consider whether the energy used to produce it is renewable, as there would be no benefit to using it if it was produced using non-renewable energy sources.

4.2. URBAN MINING INDEX

As the UMI was developed by Dr. Anja Rosen recently and its use in this edition of the SDE was pioneer, it is not easy to compare the house results with other buildings, as the use of the software is still not spread.

However, sources from the competition organisation provided information about conventional construction buildings and how they perform with the UMI, with the average value being around 30%. Therefore, it can be seen that the measures taken in the project aiming to keep materials in closed loops or, at least, open loops without a big loss of quality were actually successful.

As it is also interesting to compare the UMI results of the house with other houses which were constructed in a sustainable manner, the other houses participating in the SDE UMI results are consulted. The results range from 60 to 98 percent, with the average being around 75 percent. With the house Urban Mining Indicator being 76,6%, it is even above average of the results of a sustainable house.

As well as comparing the results of the different participants in the SDE, the most important takeaway is that there is a huge gap between sustainably built houses and traditionally built houses. As the main common denominator of all the SDE houses is the use of timber rather than concrete structures, this points the way forward for the future of construction. Timber structures have a bigger chance of being reused, and even if the use as structures is not possible anymore due to a loss of quality, wood still has potential of being used for other means.

Another interesting remark of sustainable construction an Urban Mining is that, although is not yet a widespread practice, at least compared to traditional construction, more sustainably built houses mean more sustainable and reused or recycled materials being available when these houses are dismantled, increasing the opportunities for material reuse in new projects.

4.3. CARBON FOOTPRINT

4.3.1. Construction elements.

Manufacturing phase (A1-A3): the impact during the manufacturing phase comes mainly from elements which were not recycled or reused and have a high energy consumption during manufacturing, as ceramic used on the floor and some of the walls or the windows and doors glasses. On the contrary, elements such as the wooden structure have a neutral impact on the carbon footprint, and others as the OSB boards using for the construction of the envelope modules have a positive impact. These elements make the carbon footprint of this phase the smallest of all phases.

Usage phase (B4, B6): the main elements contributing to this phase are windows and plastic sheets which must be replaced during the building lifespan. Most elements in the building will not need replacements in the 50 years projected lifespan.

Disposal phase (C3, C4): this phase is the one which contributes the most to the house carbon footprint. The main material contributing is the straw insulation, data of which was taken from the UMI database, which considers that the end of life of the product is thermal recycling. It could be argued that all renewable raw materials could be reused as long as possible and composted at some point in the future, but not burnt, but as the disposal phase will not be under control of the team that designed the project, a worst-case scenario approach was taken.

4.3.2. Technical elements.

As it is seen in "Figure 25. Final carbon footprint results", the technical elements carbon footprint surpasses the construction elements'. The main reason behind this is that, while it is easy to find sustainable materials that perform well in elements as the structure or the coverings, the development of advanced technical products needs specific characteristics that are not as common in materials. This means that specific materials should be used for some elements (for example heat pumps, solar thermal panels, batteries…) regardless of their impact.

This remarks the importance of investigation for the continued development of this products for them to be as sustainable as possible. Improvements in this fields can be seen, for example, with organic photovoltaic panels, which were used by one of the teams participating in the SDE.

Even though they are not as efficient as actual PV panels, they reduce the carbon footprint of these elements.

Even though the technical elements footprint is important, it must be considered that these elements are part of systems which contribute greatly to a demand and consumption reduction. In the case of photovoltaic panels, for example, the carbon footprint of the manufacturing is compensated in some years of usage, as the energy produced for renewable sources as the sun does not have a carbon footprint and electricity production with non-renewable sources contributes greatly to global warming.

Looking at "Figure 25. Carbon footprint final results", it is easy to see that the emissions of phase A (manufacturing) for the technical elements are lower than the energy feed-in footprint (which is negative as it is beneficial). This means that the technical elements not only reduce the footprint by reducing the consumption from the grid, but even compensate for it with the energy they feed into the grid.

In order to compare these CO2 emissions with a traditional construction house, DHW, heating and cooling related consumption data from an average house constructed after 2006 are obtained from IVE (Valencian Building Institute). As the simulations done by the team are carried out for Wuppertal, a similar climate situation needs to be found in Spain to achieve a valid comparison. There are some territories in the north of Spain which share the same Copper zone as Wuppertal. For the comparison, data from buildings in this zone are considered. The results of this comparison are shown in "Figure 26. CO_2 emissions comparison".

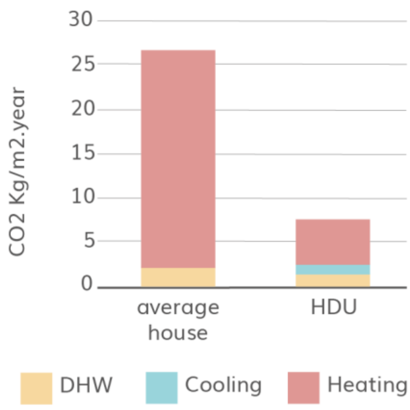

Figure 26. CO2 emissions comparison

5. CONCLUSIONS.

- Sustainability in construction is achievable: The main point of this thesis, the whole project and the SDE competition is reachable, as it is clearly proven that newly constructed buildings can be sustainable and carbon neutral.

  As more people is nowadays moving into cities and therefore new buildings are required, the sustainability of these buildings is key when considering how far we are from achieving most of the SDGs regarding climate change. The implementation of Urban Mining for materials and products to work in loops is also key, as the resources used for construction are limited and getting scarce. Also, rehabilitation and conservation should always be the priority, given the smaller impact they have compared to demolition and new construction, given that in this way new soil is not needed.

  The big role that modular construction needs to have is evident, as it works better than traditional construction improving quality, allowing standardization and making maintenance and Urban Mining easier.

- LCA and carbon footprint calculation are key tools: both the LCA and carbon footprint calculation are the main tools used both in this thesis and in construction to analyse climate impact in the most objective way. The LCA is important on buildings because it creates a path for future constructions. Also, the LCA is really useful when done on smaller products, as this allows planners to choose the best and most sustainable materials and products in the design phases.

- Innovation is key: many of the solutions proposed in our project, and in sustainable construction in general, are the result of innovation and research in various fields: development of recycled materials, structural calculations using wood instead of concrete, improvements in the efficiency of technical systems... This shows that investing in innovative projects and teaching innovation at all levels of education pays off.

- Engineering has a big role to play: although at first sustainable construction may seem as an architecture only problem, engineers have a very important role in it. The energy analysis of a building before its construction is key, as it will improve the energy performance and therefore reduce its demand. The design of systems with reduce as much as possible the energy consumption is as important, given the impact energy consumption can have in the carbon footprint.

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