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LCA OF TRADITIONAL AND TIMBER HOUSE IN ITALY

Case Study

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CONTENT

INTRODUCTION

The case study contains description of Life Cycle Assessment (LCA) methodology and evaluation of energy and environmental performance of a traditional and a timber house in Italy. Different climate contexts considered.

The case study was prepared in frames of the EU funded project "Circular Economy in Wooden Construction" (Wood in Circle), which aims at delivering innovative student-centered transdisciplinary education in circular economy-based wooden construction to postgraduate students across the European countries (https://woodincircle.eu/).

Objectives of the project:

- ✓ To integrate innovative student-centered phenomenon based, research based, blended learning and social leadership approaches into Master's degree study programmes.
- ✓ To develop a new course, educate and involve postgraduate students and teachers in scientific research on the whole life cycle of wooden construction.
- ✓ To ensure strategic transdisciplinary transnational cooperation among higher education institutions and business enterprises in development of new learning methodology and the course.
- ✓ To increase academic and public awareness and promote sustainability and circular economy in the construction sector.

1. LIFE CYCLE ASSESSMENT

About 40% of European energy consumption and most of the environmental impacts are related to the construction sector. A key role in decarbonising the construction sector play the timber buildings. Wood is a sustainable resource and has excellent thermophysical characteristics compared to traditional building materials. Today building a timber house means creating energy-efficient buildings, with high levels of bioclimatic comfort, durable, safe, and sustainable buildings. To achieve this, simultaneous energy and environmental assessment of a building is required. To date, the resolution of this complex problem is entrusted to numerous software and calculation algorithms that are often complex to use and that require the presence of expert users. From the energy point of view, several numerical approaches were developed, and most of them were tested and implemented using specialised software tools for Building Performance Simulation (BPS) such as: TRNSYS, Energy Plus, ESP-r, and DOE-2. These software programs are characterised by the lack of a common language. They describe the thermal balance by exploiting different numerical methods. These characteristics complicate the selection of the most suitable solution [1]. On the other hand, the most appropriate scientific method to measure the environmental impacts of the entire building's life (raw material supply, manufacture of construction products, construction process, usage, demolition, and/or recycling) is the Life Cycle Assessment (LCA) [2,3]. Several studies describe the LCA of a building from a theoretical point of view, whereas other papers used this methodology in analytical manner and through case studies [4,5].

The simultaneous analysis of the two aspects is fundamental to guide designers to design buildings with low impact, which consume little, which are made with ecological materials, and which base their energy needs on the almost exclusive use of renewable sources. This is green building, that is to say the building sector that pays particular attention to the issues of ecology and sustainability. The wooden house is the key building of this construction philosophy. Building a wooden house certainly has many advantages, first the material itself. In fact, wood is the natural material par excellence. The timer houses enjoy a very high level of thermal and acoustic insulation: this means that they are cool in the summer and warm during the winter months. Furthermore, all the houses built following the dictates of green building have very low energy consumption, thanks to the particularly advanced systems used in this type of buildings. In fact, many prefabricated wooden houses can boast official certifications that attest to their very low environmental impact. However, the ecological vocation of timber houses does not stop at only reduced energy consumption: at the end of their life, in fact, many are entirely recyclable and disposable without impacting on pollution. Finally, another advantage is that linked to shipbuilding. The prefabricated wooden house arrives already semi-assembled: this allows to drastically reduce construction times and to keep the construction site always clean, space-saving, and silent.

To evaluate how much a wooden house reduces consumption and therefore the impacts, a simplified procedure is proposed that allows to simultaneously evaluate the energy-environmental performance of timber houses as the climatic context varies. In particular, the performance of a building made with traditional construction will be compared with a simulated wooden building at different latitudes and climatic conditions. At the same time, a simplified assessment of one of the most important environmental index: the GWP index. For each model, thanks to a parametric analysis, the main thermophysical and geometric characteristics necessary to achieve the minimum environmental and energy comfort requirements will be identified.

2. ENERGY CONSUMPTION EVALUATION

When a building is designed, the engineer must evaluate all the exchanges that the building thermodynamic system exchanges with the surrounding environment. The goal is to create a comfortable building for the occupants.

The building is not an object, but part of an interactive and dynamic system that considers several aspects: natural (earth, water, wind, sun, vegetation) and social (identity and belonging to places) and technical (materials, elements) and geometric (position respect the sun, dimension of glazed surface),

Based on these considerations, a simplified methodology valid for residential buildings with simple geometry is proposed; more in detail it is explained the procedure to determine the heating energy demand, but the same considerations are valid for the cooling energy demand. The Primary Energy index for winter air conditioning (PE_H) to be attributed to the building can be calculated as:

$$PE_H = \frac{\left(\frac{Q_h}{A_{floor}}\right)}{\eta_{gl}}, \tag{1}$$

where:

- Q_h is the thermal energy requirement of the building during the heating period, expressed in kWh;
- A_{floor} is the useful floor area expressed in m^2;
- η_{gl} is average seasonal overall efficiency of the heating system.

The first term Q_h represents the thermal energy required by a building considering only the building system, i.e. the energy required to guarantee indoor comfort conditions. This parameter is in fact a function of the thermophysical and geometric characteristics, of the intended use, of the position with respect to the sun and of the external climatic conditions or on the border with the building.

Referring to a simplified calculation method, the entire building or an area of it (thermal zone) is examined, homogeneous for internal temperature and surrounding conditions and served by the same system; ed the calculation refers to a relatively long period: monthly or seasonal.

The main simplifying assumptions on which this method is based are the following:

- stationarity of heat exchanges within the calculation period, this hypothesis allows to assume constant values of temperatures (the average values over the period),
- one-dimensional heat flows through the building envelope elements,
- assumption of seasonal or monthly average values of climatic quantities,
- simplified evaluation of the contributions of internal and solar thermal gains.

Generally, energy requirements of a building are influenced by the transmission losses through the envelope, the energy gains due to solar radiation and the presence of people and strongly correlated to the climate context and the thermo-physical parameters. This last term is a practical index of the mean quality of the building envelope, not considering the geometry or the geographical positions of the building [6], while the weather is one of the main factors to consider when designing a building because it represents the most important boundary condition that affect the behaviour of a building.

In general, since the internal condition is different from the external condition, after it is built our building exchanges with the surrounding environment according to the temperature. For example, in the winter inside a building it is always warmer than outside.

If represent the exchanges during the heating period, i.e. when inside the house to feel good when there are 20 °C inside and outside the temperature is lower, the building exchanges as shown in the Figure 1.

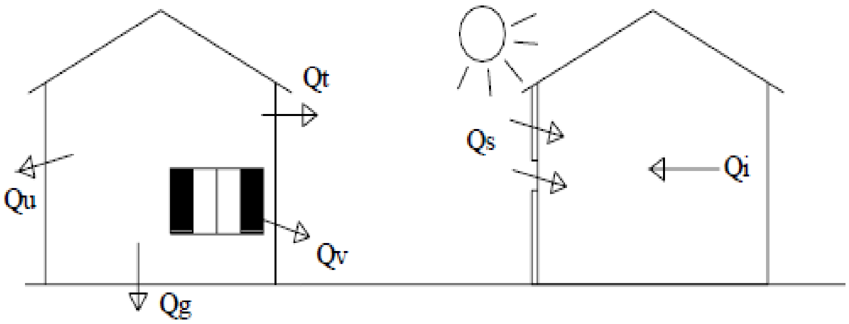

Figure 1. Building thermal balance in winter

The building is therefore the reference system, and the outline of the building represents the boundary between the internal system and the surrounding environment. Through the boundary, i.e. the building envelope, there will be outgoing and incoming heat flows. The flows that leave the building system are losses, the flows that enter are gains.

The equation that represents the thermal energy demand in winter is:

$$Q_h = 0.024\, HDD\, Q_T - \eta_x Q_G, \tag{2}$$

where:

- 0.024 is a correction coefficient for the measurement units, that permit to obtain kWh
- HDD is the Heating Degree Days [°C/day];
- Q_T is the thermal transmission losses of the building;
- Q_G is the thermal gains of the building;
- η_x is the utilization factor, a parameter that has the function of compensating for the additional losses that occur when the thermal gains are greater than the losses; in this case is equal to 0.95.

The HDD is a measurement designed to quantify the demand for energy needed to heat a building. It is the number of degrees that a day's average temperature is below 65o Fahrenheit (18 Celsius), which is the temperature below which buildings need to be heated; in general, higher is the HDD value, colder the climate will be. Each city is represented by an HDD and the official values of this are tabulated in specific technical standards.

In this simplified procedure the Q_T is calculated as the sum of:

$$Q_T = H_T + Hv, \tag{3}$$

where:

- H_T: is the global coefficient of heat transfer by transmission, to consider the internal-external temperature difference of each dispersing surface, and is measured in $\left[\frac{W}{K}\right]$;
- H_V: is the global coefficient of heat exchange for ventilation $\left[\frac{W}{K}\right]$.

More in detail, the H_T is equal to:

$$H_T = \sum_{i=1}^{n} S_i * U_i * b_{tr,i}, \tag{4}$$

where:

- S_i: external surfaces that enclose the gross heated volume. Surfaces to other rooms heated to the same temperature are not considered $[m^2]$;
- U_i: thermal transmittance of the structure $\left[\frac{W}{m^2K}\right]$;
- $b_{tr,i}$: correction factor of the heat exchange towards non-air-conditioned environments or towards the ground (dimensionless) (is from 0.1 to 0.9).

The *Hv* is equal to:

$$H_V = 0{,}34 * n * V_{net}, \tag{5}$$

where:

- n: number of air changes and for residential building is equal to $0.3\ \mathrm{vol/h}$;
- V_{net}: net volume of the air-conditioned environment assumed equal to 70% of the gross volume.

About the second part of the equation, the thermal gains Q_G of the building, it is equal to:

$$Q_G = Q_S + Qi, \tag{6}$$

where:

- Q_s are the Solar gains through the transparent envelope components;
- Q_i is the internal gains.

The solar gains Q_s are determined by the formula indicated as a function of the total solar radiation and the size of the window corrected by a coefficient 0.2 which takes into account the elements that reduce solar radiation such as: shutters, blinds, curtains, obstructions, overhangs.

$$Q_s = 0{,}2 \sum_{exposure} I_{sol,i} * S_{win,i}, \tag{7}$$

where:

- $I_{sol,i}$ is the total seasonal irradiance (in the heating period) in the vertical plane, for each exposure [MJ/m^2];
- $S_{win,i}$: is the global window surface for each exposure expressed in m^2.

Summarizing the thermal energy of a building Q_h is equal to

$$Q_h = 0{,}24\,GG(H_T + H_V) - f_x(Q_s + Q_i). \quad (8)$$

As regards the determination of the overall efficiency of the heating system, this is obtained as a product of the 4 performances of the subsystems representing the heating system, i.e .:

$$\eta_{gl} = \eta_e * \eta_r * \eta_d * \eta_g, \quad (9)$$

where:

- η_e: emission efficiency;
- η_r: regulation efficiency;
- η_d: distribution efficiency;
- η_g: generation efficiency.

All these values are tabulated in technical standards or indicated in the technical data sheets of the elements, they depend on the type of system installed and all have values between 0 and 1.

3. ENVIRONMENTAL IMPACTS PROCEDURE

As far as the environmental impact assessment is concerned, in this simplified procedure only the GWP index was evaluated. Global-warming potential, abbreviated as GWP, is a term used to describe the relative potency, molecule for molecule, of a greenhouse gas, taking account of how long it remains active in the atmosphere. The global-warming potentials (GWPs) currently used are those calculated over 100 years. Carbon dioxide is taken as the gas of reference and given a 100-year GWP of 1. A simplified calculation for the determination of this parameter provides for the application of the following equation:

$$GWP_b = \sum_1^n q_i * I_i, \tag{10}$$

where:

- q_i: quantity (mass or volume or area) of the i-material in the building component b (m^3 or m^2 or kg);
- I_i: specific impact of the i-material on the GWP ($kgCO_{2eq}/m^3$ or $kgCO_{2eq}/m^2$ or $kgCO_{2eq}/kg$).

To determine the global GWP of an element it is necessary to follow three main steps:

1) First step: calculation of qi for each building component b

If the specific impact of the *i*-material is expressed in m^3 (this applies to wood): starting from the area and thickness of each *i*-material of the building component b you can calculate the volume of the *i*-material.

If the specific impact of the *i*-material is expressed in m^2 (this applies to window frame): starting from geometry of the *i*-material of the building component b you can calculate the area.

If the specific impact of the *i*-material is expressed in kg (this applies to all the materials/components except for wood and window frame): starting from the area and thickness of each *i*-material of the building component b and using the density of the material (search on internet) you can calculate the mass of the *i*-material.

2) Second step: identification of I_i for each *i*-material.

For example, in the following Table 1 below shows the specific impact on GWP for different materials that can be used in the building.

Table 1. Specific impact on GWP for different materials

Material	**GWP**	**Unit of measure**
Flat glass	1,16E+00	kg CO_2eq/kg
Gypsum plasterboard	3,43E-01	kg CO_2eq/kg
Stone wool	1,28E+00	kg CO_2eq/kg
Lime	4,18E-02	kg CO_2eq/kg
Cellulose fibre	2,53E-01	kg CO_2eq/kg
Glass wool mat	2,65E+00	kg CO_2eq/kg
Polystyrene foam slab	4,46E+00	kg CO_2eq/kg
Synthetic rubber	2,33E+00	kg CO_2eq/kg
Window frame, aluminium	6,64E+02	kg CO_2eq/m^2
Window frame, poly vinyl chloride	2,73E+02	kg CO_2eq/m^2
Window frame, wood	1,41E+02	kg CO_2eq/m^2
Fibreboard	8,65E+02	kg CO_2eq/m^3
Structural timber	9,09E+01	kg CO_2eq/m^3

For each *i*-material of the building component *b* select the material in the list below (if you can't find the same material, identify a similar material).

3) Third step: calculate the GWP for each building component *b* and for the whole building appling the formula: $GWP_b = \sum_1^n q_i * I_i$.

4. CASE STUDY

To highlight how energy consumption and the related environmental impact is closely linked to the type of building that is designed and used, the following report analyses the energy and environmental performance of a building through the two simplified procedures described above.

In detail:

1) the performance of a residential building designed according to the traditional typology of load-bearing masonry houses will be analysed.
2) the same building will be redesigned in wood, to evaluate how this type of building has a great benefit on consumption and therefore on the environment.
3) Finally, to assess how the climate plays an important role in these assessments, the performance of the same building at different latitudes will be analysed through a parametric analysis.

4.1. Energy and Environmental performance of a traditional house in Italy

As indicated above, to evaluate how the characteristics of a building and its design affect energy consumption and therefore the environmental impact, it was decided to analyse the energy-environmental performance of a traditional house built in Italy.

It is assumed to consider a residential house of simple geometry, built with traditional materials, that is with reinforced concrete structure, external walls in perforated bricks, aluminium frames and double glazing, insulated attic with simple sheath, with an uninhabited attic and ending with a double pitched roof with tiles.

The main parameters that represent this house are collected in the following Table 2.

Table 2. Main parameters of traditional house case study

Wall	**Transmittance [W/m²K]**	**Surface [m²]**	**Losses [W/K]**
External Walls	1.13	92.4	104.92
Roof	0.95	80	53.2
Floor	1.2	80	43.2
Window	1.7	13.8	23.46

For winter air conditioning the presence of a system with gas boiler and radiant plates was considered.

The house is in Rome, an Italian city characterized by a temperate climate; the HDD of Rome is 1451 and the heating period is from 1st November to 15th April. Knowing the position from a climatic point of view is fundamental, the flows into and out of the building system depend on the external climatic conditions. The temperature and solar irradiance distribution related to Rome are represented in the following Figures 2 and 3.

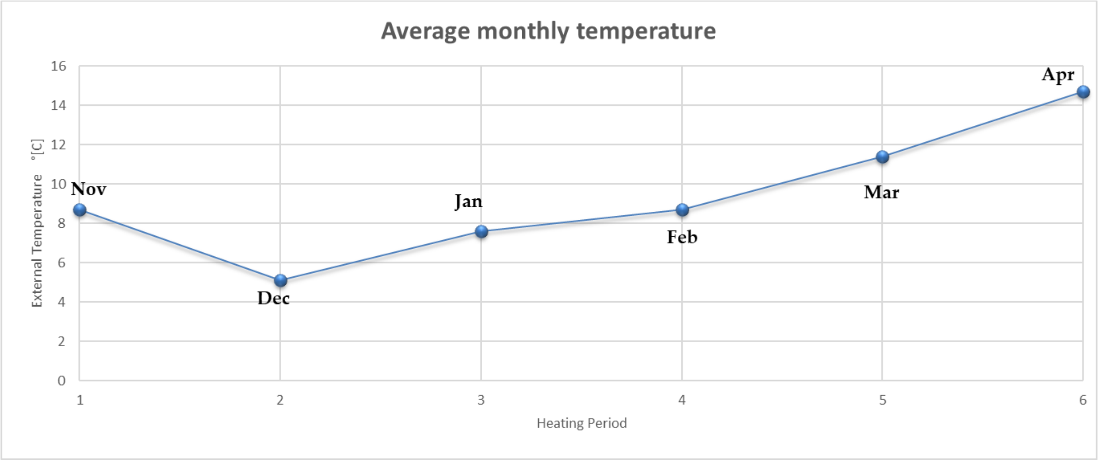

Figure 2. External temperature trend in Rome

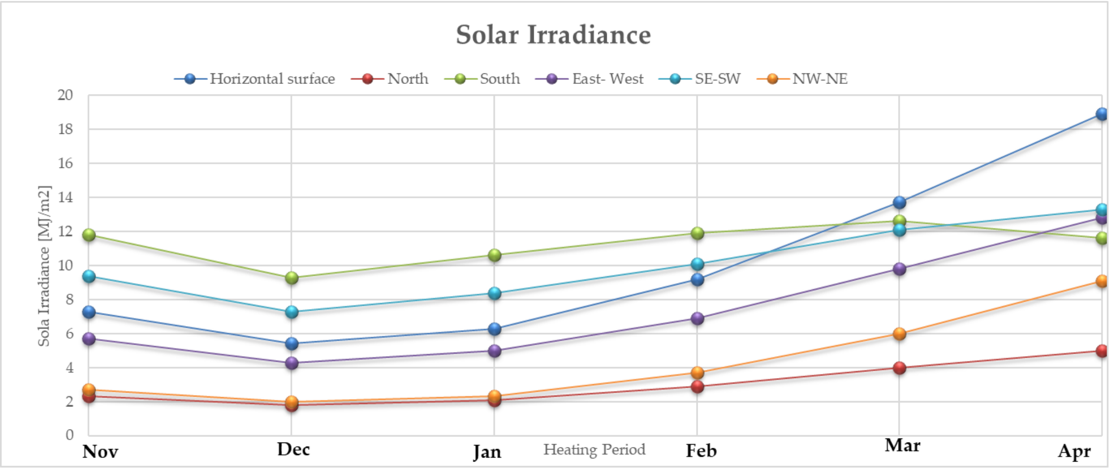

Figure 3. Solar Irradiance trend in Rome

Collecting all fundamental data such as geometric distribution and dimensions, weather conditions, materials. positions and stratigraphy of each dispersing surface and calculating the respectively transmittance values, it was possible to determine the following results:

- Heat Losses (H_T) = 224.27 W/K;
- Ventilation Losses (H_v)= 19.58 W/K;
- Solar Gains (Q_s): 705.9 MJ= 192.38 kWh;
- Internal Gains (Q_i): 928 kWh;
- Average Seasonal efficiency (h_{gl})=0.78.

That permits to calculate a Primary Energy value equal to **PE= 170 kWh/m^2 year**.

The application of the procedure about the calculation of the Global Warning Potential in the traditional house in Rome, determines a global **GWP =20132 kgCO$_2$**.

A building emits CO$_2$ emissions not only during its construction, but also during its use.

Assuming a life of 50 years, we can also calculate the GWP relating to the heating of the building under analysis, considering the plant system used, that is a methane gas boiler. It is therefore necessary to calculate how much energy a building needs during the heating period and then evaluate how many kilograms of CO_2 the heat generator emits for each unit of heat energy in a building.

In this case study, neglecting the CO_2 emissions related to the extraction, supply, transport and distribution of gas; emissions will only be caused by the combustion of the natural gas itself.

The estimate of the quantity of natural gas needed in the 50 years is equal to:

$$V_{CH_4} = \frac{\frac{(Q_h)}{\eta_{gl}}}{LHV_{CH_4}},$$

where LHV_{CH4} is the Lower Heating Value of natural gas.

Knowing that the combustion of 1 m^3 natural gas emits approximately 1.95 kg of CO_2:

$$GWP_{using} = V_{CH_4} * \mu_{CO_2,CH_4} = 86653 \text{ kg } \mathrm{CO_2},$$

where $m_{CO2,CH4}$ is the density value equal to 1.95 kg/m^3. In this way the **overall GWP** of the building and its usage is equal to **106183.11 kgCO$_2$**.

4.2. Energy and Environmental performance of a timber house in Italy

To evaluate how the same building, made of wood, allows for a reduction in consumption and therefore on the environmental impact, it was designed like a wooden house.

Leaving the geometry and position with respect to the sun unchanged, it was assumed that:

- the external walls are made of wood with the presence of rock wool panels and X-Lam wood panels;
- the floor has a low impact insulating structure with wooden floor;
- the external covering foresees a ventilated structure with wood fibres;
- the windows are made of wood with double glazing.

The main characteristics of these surfaces are collected in the following Table 3.

Table 3. Main parameters of Timber house case study

Characteristics	**Timber House**
Wall Transmittance	0.12
Roof Transmittance	0.11
Floor Transmittance	0.49
Window Transmittance	0.93

It was possible to determine the following results:

- Heat Losses (H_T)= 66.61 W/K;
- Ventilation Losses (H_v)= 17.14 W/K;
- Solar Gains (Q_s): 705.9 MJ= 192.38 kWh;
- Internal Gains (Q_i): 928 kWh;
- Average Seasonal efficiency (h_{gl})=0.78.

That permits to calculate a Primary Energy value equal to **PE= 38.5 kWh/m^2 year**, that is, the same building with the same intended use but made entirely of wood has a primary energy requirement 4 times lower.

The application of the procedure about the calculation of the Global Warning Potential in the traditional house in Rome, determines a global **GWP =11396 kgCO$_2$; w**hile the **overall GWP** is equal to **30994 kgCO$_2$.**

In terms of overall GWP a wooden house is better because the GWP related to construction is lower than the traditional house due to the lower specific impact of wooden materials and the GWP related to use is lower because the primary energy consumption is lower. thanks to a better building envelope.

4.3. Energy and Environmental performance of a house in different climate context

As already indicated, the climate is a parameter that strongly influences the performance of a building, thus highlighting how it is not possible to create the same building with the same thermophysical characteristics, the same system, and the same glazed surfaces for all latitudes.

To highlight this phenomenon, the energy and environmental performance of the traditional building and the wooden one in three different climatic contexts of the Italian peninsula will be analysed in the following paragraph.

4.3.1. Climate context

Italy is a peninsula located in the centre of the temperate zone of the northern hemisphere that also includes two large islands: Sicily and Sardinia. Generally, it is possible to identify three big climate areas: in the north the climate is harsh, with very cold winters and very hot and particularly humid summers, due to the presence of Alps and Apennines. In central Italy, the climate is milder and a shorter and less intense cold season respect in the north; summers are longer, but the sultriness of the northern cities is mitigated by the sea. In southern Italy and the islands, winters are never particularly harsh, and spring and autumn temperatures are like those reached in the summer in other areas of Italy. According to the Italian national guidelines for buildings energy certification, it was possible to identify different climatic zones that (theoretically) have the same climate [7]. Employing the HDD, it is possible to identify six different climatic zones: zone A represents the hottest one and zone F represents the coolest. In the following Figure 4 and Table 4 for each zone, it is issued the daily hours of the heating system activity and the consequent yearly period [8].

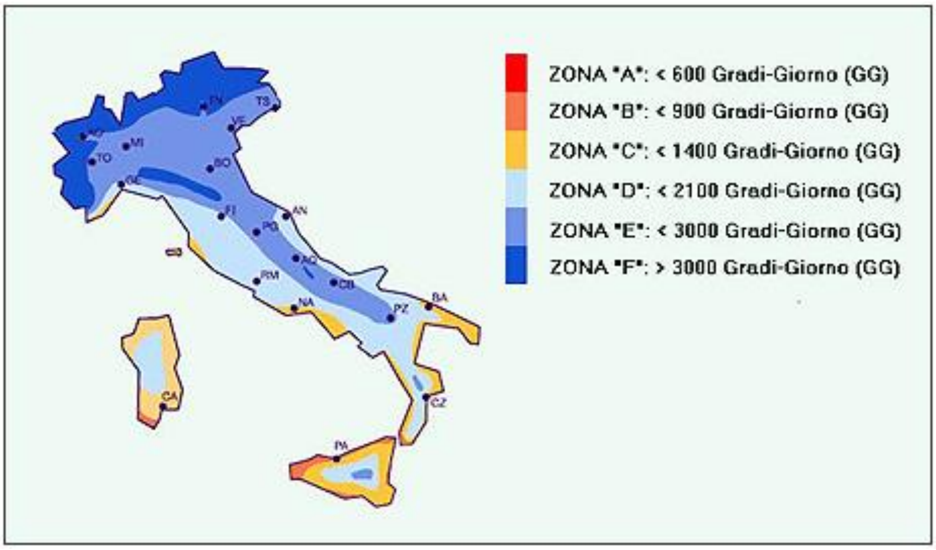

Figure 4. Italian Climatic zone [9]

Table 4. Parameters of the Italian Climatic zone

Climatic Zone	**From HDD**	**To HDD**	**Heating season**		**Daily hours**
			From	To	
A	0	600	1st December	15th March	6
B	601	900	1st December	31st March	8
C	901	1400	15th November	31st March	10
D	1401	2000	1st November	15th April	12
E	2101	3000	15th October	15th April	14
F	3001	∞	No limit		

4.3.2. Building in different Climate context

In this case it was decided to analyse and compare the energy and environmental performance of the traditional house and the timer house in three different Italian cities:

- Bologna, HDD= 2259, Climatic Zone= E;
- Roma, HDD=1451, Climatic Zone= D;
- Palermo, HDD= 751, Climatic Zone= B.

The weather data related the cities are represented in the following Figures 5–8.

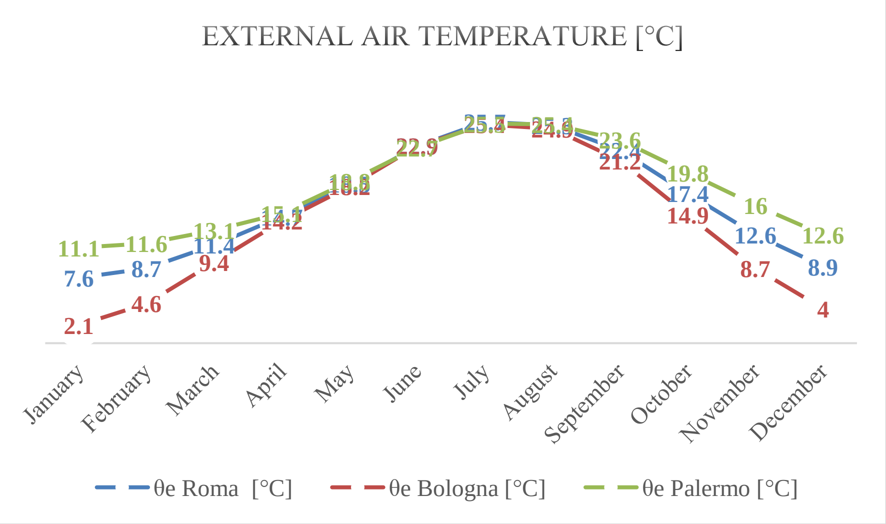

Figure 5. External air temperature of three Italian cities

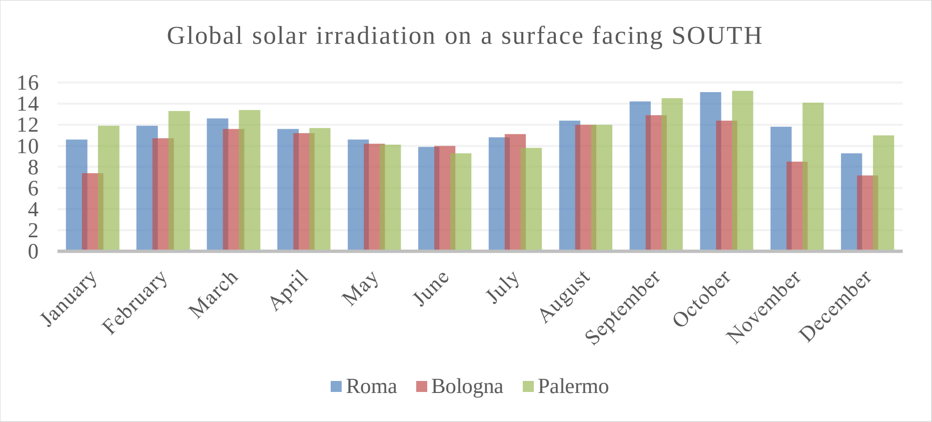

Figure 6. Global Solar Irradiance on South of three Italian cities

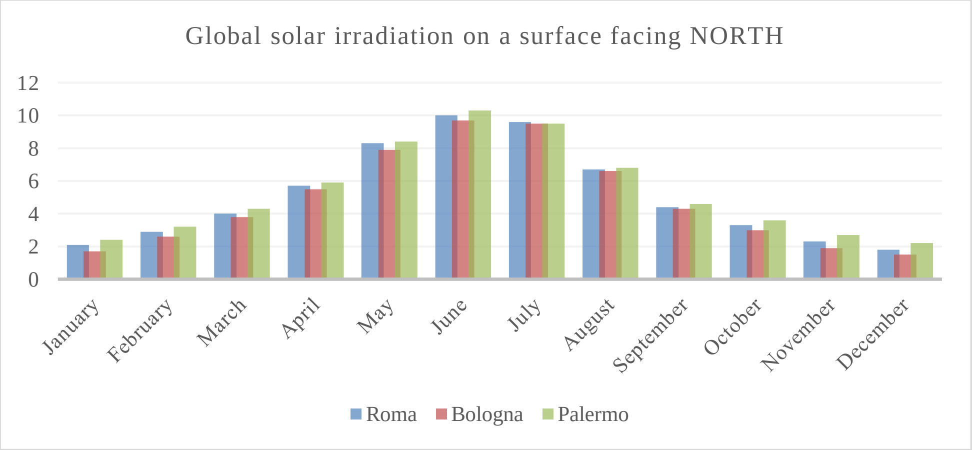

Figure 7. Global Solar Irradiance on North of three Italian cities

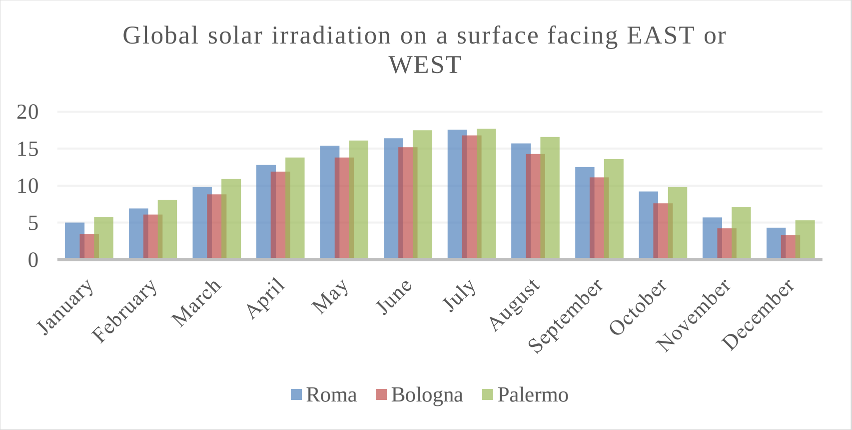

Figure 8. Global Solar Irradiance on East and West of three Italian cities

4.3.3. Energy and Environmental performance

Changing the climatic context in which the building is located, the heating demand will be different, so the primary energy needed for heating will also be different.

The results obtained, for traditional and timber house, are in fact the following Table 5.

Table 5. Comparison of PE of traditional and timber house in different climate context

	PE in each city [kWh/m^2year]		
	Bologna	Roma	Palermo
Traditional House	269.06	17.34	87.43
Timber House	63.84	38.53	19.28

Obviously, more critical the external weather conditions, greater is the primary energy needed for heating period.

It is therefore clear how the thermophysical design of a building must be strictly connected to the climatic context. For example, the building located in Bologna would need a greater thickness of insulation than the building located in Rome, while the one in Palermo required less insulation.

But, regardless of the geographical location, in this example the choice of a wooden house rather than a concrete one has a reduction of about 77% of the primary energy needed for heating period (Figure 9). By changing the climate context, we have seen a big change in the primary energy needed for heating, so there will be a change in the GWP linked to the use of the building.

The results are represented in the following figure which shows how the choice of a wooden house rather than a concrete house leads to a reduction in CO_2 emissions equal to:

- 71% in Rome;
- 73% in Bologna;
- 67% in Palermo.

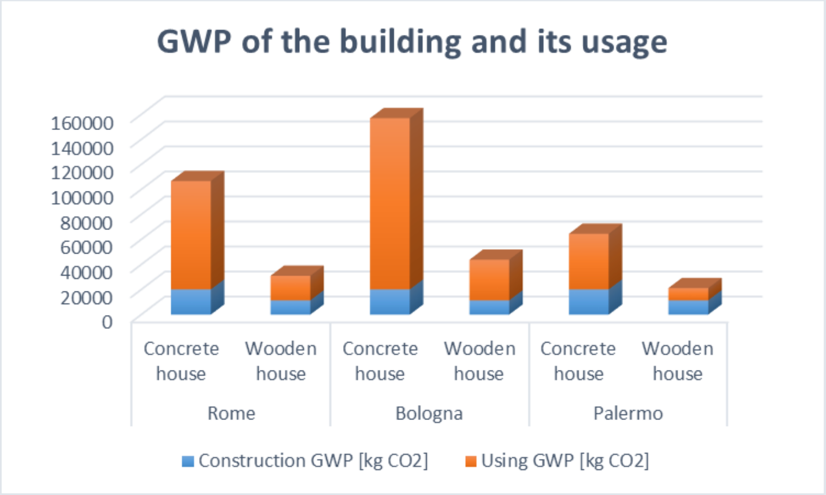

Figure 9. Comparison of overall GWP of traditional and timber house in different climate context

CONCLUSION

In this report, using a simple procedure, it was possible how the design of buildings and the choice of materials play an important role in reducing consumption and environmental impacts.

The analysis carried out for the winter period can be extended to the summer one. Wooden houses represent a key solution for solving this problem, guaranteeing the creation of safe, comparable, and low-impact houses.

Obviously, it represents only a generic evaluation that can be integrated and refined.

The climate is a fundamental parameter in these assessments, in fact a more specific analysis would allow to find doc solutions, both from the point of view of transmittance and from the plant engineering point of view, or specific solutions for a specific project, in a specific climatic context and with specific geometry and position with respect to the sun. For example, by identifying the correct thickness of insulation or the best system for air conditioning; or the increase in the overall efficiency of the air conditioning system from 0.78 to 0.98 allows the energy requirement to be reduced by about 22% and therefore significantly reduces the environmental impact. The greater the reduction if integration with renewable source systems or systems in which the energy carrier is of the electric type is assumed.

Finally, it is obvious that a complete assessment of these aspects cannot lack an analysis of the economic aspects, which also considers the recyclability of the materials.

In any case, the objective of the proposed case study highlighted how wooden houses are a key solution to environmental impact problems and how therefore the designers of tomorrow must focus on these aspects by studying and proposing green and low-impact and circular solutions, to meet the needs of a cleaner and more sustainable world.

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