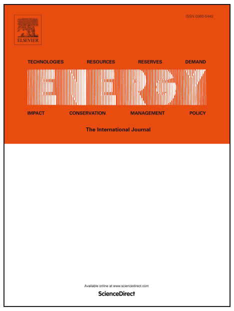

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# Dynamic Life Cycle Assessment modelling of a NZEB building

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***Abstract***.

Most of the developed countries are struggling to reduce carbon emissions into the atmosphere to meet the international agreements. One of the strategies to reduce climate change impacts is the decarbonisation of the electricity production: generation mixes are more and more based on renewable energy sources that are replacing the traditional fossil fuels.

The effect of the electricity decarbonisation production reflects in the life cycle impacts of buildings, particularly if they are strongly dependent on the electrical energy as the main energy vector. The traditional Life Cycle Assessment (LCA) cannot capture the effect of lowering emission factors for electricity generation since only static values are considered. Moreover, also the grid-building interaction should be properly taken into account in the life cycle assessment of buildings using dynamic calculations. A dynamic life cycle analysis is the methodology that can overcome these limitations through the introduction of dynamic parameters within the life cycle inventory and in the life cycle impact assessment stages.

A Dynamic Life Cycle Assessment (DLCA) is proposed in order to evaluate the consequences of electricity decarbonisation on the LCA of an "all electric" Nearly Zero Energy Building (NZEB). A comparison with literature results about similar constructions is finally provided.

**Keywords:** Dynamic LCA; NZEB; Decarbonisation scenarios; Carbon Intensity; Electricity production.

**Nomenclature**

| | |
|---|---|
| CED [kWh] | Cumulative Energy Demand |
| CI [kg $CO_2$-eq/kWh] | Carbon Intensity |
| CPS | Current Policy Scenario |
| DLCA | Dynamic Life Cycle Analysis |
| DQI | Data Quality Index |
| EC | Embodied carbon |
| $EF_m$ [kg $CO_2$-eq/kWh] | Emission Factor for Gross Electricity Production |
| $EF_{NFE}$ [kg $CO_2$-eq/kWh] | Emission Factor for Imported Electricity |
| $EF_t$ [kg $CO_2$-eq/kWh] | Emission Factor for Thermoelectric production |
| EoL | End of Life |
| EPBD | Energy Performance of Building Directive |
| EPD | Environmental Product Declaration |
| Fe [kWh] | Final Energy |
| GHG | Greenhouse Gases |
| $GHG_{op}$ [kg $CO_2$-eq] | Greenhouse Gases (operational stage) |
| $GHG_{up}$ [kg $CO_2$-eq] | Greenhouse Gases (upstream stage) |
| GWP [kg $CO_2$-eq] | Global Warming Potential |
| HVAC | Heating, Ventilation and Air Conditioning |
| IPCC | Intergovernmental Panel on Climate Change |
| LCA | Life Cycle Analysis |
| LCI | Life Cycle Inventory |
| LCIA | Life Cycle Impact Assessment |
| LMI | Load Match Index |
| LV | Low Voltage |
| NFE | Net Foreign Exchange |

| | |
|---|---|
| NPS | New Policy Scenario |
| NZEB | Net or Nearly Zero Energy Building |
| PV | Photovoltaic |
| PCR | Product Category Rule |
| REP | Renewable Electricity Production |
| RER | Representing Europe |
| SDS | Sustainable Development Scenario |
| Self-C | Self-Consumption of Power Plants |
| TE | Thermoelectric Production |
| U-value [W/(m$^2$K)] | Thermal Transmittance |
| WEO | World Energy Model |

## 1. Introduction

The Paris agreement [1] requires the 195 subscribers countries to hold global temperatures to a maximum rise of 1.5 °C above pre-industrial levels. Within this goal, the retrofit of the building stock becomes a key issue since it is responsible for a significant share of the world's energy consumptions and greenhouse gas emissions [2].

The effort of legislations and designers is principally focused on the reduction of energy consumptions in the operational stage of the constructions since they represent the largest amount (between 60% and 90% of the total in traditional buildings [3−6]) and because the energy efficiency can lead to a considerable reduction of the life cycle energy. Considering the life cycle carbon footprint of 251 case study buildings, Schwartz et al. [7] showed that embodied, operational and demolition carbon are, on average, respectively the 24%, 75% and 1%, of the total. The highest contribution of the operational emissions in traditional buildings is confirmed by different other authors: 90% for Franca and Azapagic [8] and Scheuer et al. [9].

The installation of renewable energy systems able to substitute the traditional fossil fuels was found to be another solid environmental friendly solution with competitive economic and environmental payback times [10−12].

The European legislation and the consequent national laws are moving towards this direction introducing the Nearly Zero Energy Building (NZEB) as the minimum standard for new constructions for the next years [13].

The design of these building typologies necessarily increases the embodied impacts of the constructions. Ramesh et al. [4] highlighted how the energy incorporated in buildings with low energy consumption approaches 45%. In a low energy building located in Milan [14] the use stage is responsible for only the 31% of the total impacts while the production and maintenance stages account for the 56% of the total impacts. For Dodoo et al. [15] the embodied carbon of low energy buildings is over the 60%.

The potential burdens shifting makes a complete life cycle analysis of impacts recommendable and for this reason the interest on the LCA methodology is spreading [10,12,16,17]. Its application becomes strongly relevant when studying the energy and carbon balance of NZEBs [18,19].

The rising importance of the production stage in the building's life cycle is reinforced by the decarbonisation of electricity production since it can sensibly reduce the incidence of the use stage in a building fed with electricity as main energy vector. In 2016, 17.4% of the Italian final energy consumption was covered by renewable resources while 34% of the electricity was produced by renewables [20]; the percentage of energy derived from renewable technologies is rising also due to the diffusion of government feed-in tariffs [21] that incentivize the decarbonisation: +9.9% in comparison to the level registered in

2005, +4.4% taking into account 2010 [20]. The energy mix used for buildings needs changes over time and it is also different from the one employed to produce construction materials [22].

Furthermore, intra-annual variations of the electricity mix can be detected at seasonal, daily or hourly level. For example, PV generation is concentrated in some hours of the day while at night it is absent and significant variations can also be detected at seasonal level with a higher production in summer and a reduced generation in the winter months. These variations are increased in a decarbonisation scenario and if on-site generation with self-consumption is introduced, such as in NZEBs.

The decarbonisation modelling of a national energy mix and the inclusion of hourly energy mixes necessarily imply the application of a dynamic LCA, which is still a research topic.

Collinge et al. [23] defined the dynamic LCA “as an approach to LCA which explicitly incorporates dynamic process modelling in the context of temporal and spatial variations in the surrounding industrial and environmental systems”. Buildings are complex systems that are subjected to a lot of changes during their long lifetime: this issue endorses the importance of the dynamic approach. The question that arises is about the main variable parameters which need to be considered in the dynamic modelling.

Negishi et al. [24] proposed an original time dependent methodology that enable to evaluate the temporal behaviour of a building considering variations in the technologies (e.g. temporal degradations of insulations or improvements in technological properties of substituted elements), occupant behaviours, energy mixes and legislative regulations. Su et al. [25] introduced four variable properties in a DLCA: the technological progress, the variation in occupancy behaviour, dynamic characteristic factors and dynamic weighting factors. Fouquet et al. [26] proposed a DLCA that takes into account biogenic carbon and underlines the importance of considering the timing of carbon sequestration and of releasing of GHG emissions as suggested by Levasseur et al. [27].

Roux et al. [28−30] showed that climate change, future energy mixes and their intra-annual temporal variation can have a powerful influence in the results obtained using a traditional LCA methodology.

In Table 1 are listed the dynamic parameters taken into account by the analysed literature.

**Table 1.** Summary of Dynamic LCA studies.

| Authors | Year | Dynamic field | Object | Pros and cons | Comments |
|---|---|---|---|---|---|
| Collinge et al. [23] | 2013 | Dynamic LCI | Technological progress | DLCA results have increased relevance. | Results of DLCA and static LCA can be very different. |
| | | Dynamic LCIA | Weighting factors | | |
| | | Dynamic LCIA | Characterization factors | | |
| Su et al. [25] | 2017 | Dynamic LCI | Technological progress | DLCA results have a higher accuracy in building applications because of their long life. | The DLCA is seen as a promising tool for building sustainability evaluations. |
| | | Dynamic LCI | Occupancy behaviour | | |
| | | Dynamic LCIA | Weighting factors | | |
| | | Dynamic LCIA | Characterization factors | | |
| Negishi et al. [24] | 2018 | Dynamic LCI | Technological progress | DLCA permits to overcome the limitations of the static LCA in evaluating systems with a long life time. | A new tool for DLCA is proposed. |
| | | Dynamic LCI | Occupant behaviour | | |
| | | Dynamic LCI | Energy mix | | |
| | | Dynamic LCI | Regulations | | |
| Fouquet et al. [26] | 2015 | Dynamic LCIA | Biogenic carbon | DLCA allows a more consistent analysis but increases uncertainty. | A high uncertainty in predicting future data is underlined but DLCA can help decision makers recognizing potential impact scenarios. |
| Moran et al. [31] | 2017 | Dynamic LCIA | GWP characterization factor | DLCA permits to incorporate a future increase of grid efficiency and some decarbonisation scenarios; the assumptions lack of a real calculation support. | The DLCA remains a sensitivity analysis about future variations of electricity generation scenarios. |
| Pehnt [32] | 2006 | Dynamic LCI | Production processes innovations, efficiency improvements, increased life | DLCA permits to analyse what is the potential improvement of | The improvement potential is strongly context and |

| | | | | | |
|---|---|---|---|---|---|
| | | | time, emissions characteristics | renewable technologies against the competitors. | technological dependent. |
| C. Roux et al. [30] | 2016 | Dynamic LCI and LCIA | The effect of future variations in external climate and energy mixes is captured. | The novel approach guarantees a higher robustness and realism. The introduction of prospective scenarios increases uncertainty. | Climate change and future energy mixes can strongly influence LCA results. |
| C. Roux et al. [29] | 2016 | Dynamic LCIA | Hourly characterization factors | The dynamic model reduces the errors due to the use of a yearly average mix but increases calculation complexity. | Temporal variation of electricity production can deeply influence the LCA outputs. |

Due to the long lifetime of the buildings, the results obtained using a dynamic method can widely differ compared to the ones of the static LCA. For instance, Collinge et al. [23] found a reduction of more than 50% of the impacts related to air pollutants: a dynamic temporal modelling of some LCA parameters increased the reliability of the results. Therefore, in a decarbonisation scenario of the electricity production, a dynamic LCA modelling becomes very interesting especially when "all electric" buildings are under evaluation [33]. De Wolf et al. [34] showed that decarbonisation is only occasionally taken into account in the LCA analysis and frequently the practitioners use current national energy mixes also for future scenarios.

When, instead, considering the temporal mismatch between loads and generation in buildings it is useful to properly take into account the interaction between the local renewable energy production systems and the power grids. As shown by Roux et al. [29], the use of an annual averaged energy mix value in place of hourly data can lead to an underestimation of the total potential impacts of the 39% for Abiotic Depletion Potential and of the 36% for Global Warming Potential. The DLCA is a useful methodology that is able to refine the outputs of the traditional method and increase their robustness. However, only in few literature studies introduce intra-annual variations of the electricity mix in the LCA calculations.

This paper aims at evaluating the effects of some methodological assumptions in the LCA of a low energy building chosen as case study. In particular the sensitivity of the traditional LCA to some decarbonisation scenarios and to different sampling frequencies in the energy and carbon modelling is checked. The introduction of inputs whose values are dependent on time involves the method called dynamic life cycle assessment (DLCA). The study reviews the literature about the topic of DLCA and then introduces the methodology adopted for the life cycle analysis, the energy monitoring and the hypothesis made for the decarbonisation scenarios considered and for the calculation of the carbon intensities. After that the case study is introduced - an "all electric" building - which was chosen since it is significant for the purpose of the analysis.

## 2. Methodology - *LCA assumptions*

The standards ISO 14040 [35] and 14044 [36] define four LCA principal steps:

- Definition of the goal and scope of the analysis
- Life Cycle Inventory (LCI)
- Life Cycle Impact Assessment (LCIA)
- Interpretation of the results

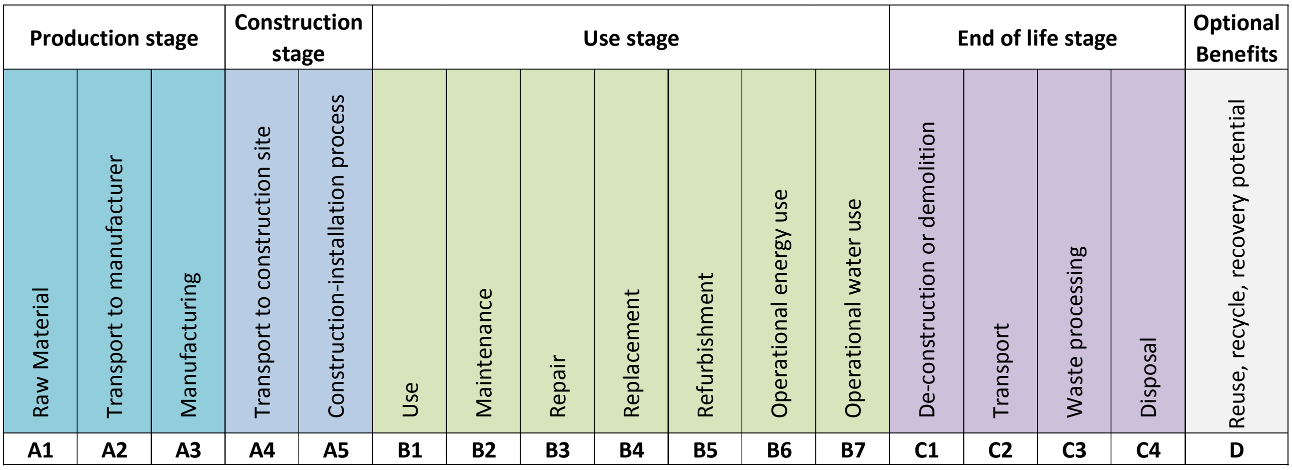
The four steps are not in a rigid time succession but can be interrelated in an iterative approach where it is possible to adjust and change the assumptions made during the previous steps. In our case study, the scope of the analysis is to evaluate the energy and carbon impacts related to the construction of a building and the effect of a decarbonisation scenario on them. The definition of the purpose implies also the explanation of the boundaries of the analysis: time frame, functional unit, data quality requirements, impact categories to be considered.

The PCR scheme [37] has been employed in the study for the definition of the boundaries and of the life cycle stages of the analysis. Fig. 1reports the life cycle stages for a new building. Referring to the PCR, the time frame chosen is equal to 50 years; in order to cancel the dependence of the results on the building size, they are reported per square meter of gross internal area, as indicated by the PCR; moreover, the necessity of a harmonization with other literature studies brought to the necessity of a normalization of the cumulative environmental burdens by year. The choice of a 50 years life span of the building can have a strong influence on the relative contribution of the different life cycle stages in the total environmental burdens; very different assumptions on the life span of the buildings are made in literature and so the value prescribed by the PCR is employed.

In this study we included biogenic carbon of wood elements as a negative value of the GWP in the production stage.

We instead neglected the impacts or benefits connected to the stages B1-B3-D while we included replacement of the building elements considering the service life suggested by the EN 15804 [38]: 35 years for windows and insulation materials, 25 years for wall linings, 10 years for wall coverings, 20 years for services. If the transport was not already included in the Ecoinvent processes, we supposed a distance of 60 km for transportation to the construction site (A4 stage). Different transport means have been considered: light diesel-fuelled commercial vehicles for panels and prefabricated materials, 32 tonnes truck for the concrete mixer. The energy consumptions linked to the stage A5 are considered negligible since the construction site is very small and a superficial foundation, without any deep excavation process, characterizes the building. Stage B7 is also neglected since the building analysed is not equipped with water distribution systems.

The end-of-life stage has been included in the analysis: aluminium, glass, steel and copper elements are recycled, reinforced concrete is partially recycled (0.582 kg/kg of reinforced concrete [39]) after the separation from steel and wood components are incinerated (the total biogenic carbon is released by the combustion of wood wastes).



| Production stage | | | Construction stage | | Use stage | | | | | | | End of life stage | | | | Optional Benefits |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Raw Material | Transport to manufacturer | Manufacturing | Transport to construction site | Construction-installation process | Use | Maintenance | Repair | Replacement | Refurbishment | Operational energy use | Operational water use | De-construction or demolition | Transport | Waste processing | Disposal | Reuse, recycle, recovery potential |
| **A1** | **A2** | **A3** | **A4** | **A5** | **B1** | **B2** | **B3** | **B4** | **B5** | **B6** | **B7** | **C1** | **C2** | **C3** | **C4** | **D** |

**Fig. 1.** LCA stages as reported in the PCR [37].

The highest possible data quality has been researched and a Data Quality Index (DQI) has been proposed [40,41]. The DQI gives a subjective evaluation of the quality of the data used based on the indicators reported in Table 2: temporal correlation, geographical correlation and technological correlation.

**Table 2.** Data quality indicators [40].

| | 1 (high) | 2 (medium) | 3 (low) |
|---|---|---|---|
| Temporal correlation | Less than 3 years | Less than 10 years | Unknown or more than 15 years |
| Geographical correlation | Data from area under study | Data from area with similar production conditions | Data from unknown area with different production conditions |
| Technological correlation | Data from enterprises, processes and materials under study | Data from processes and materials under study but from different technology | Data from related processes and materials but different technology |

In order to maximize the data quality, the following precautions were taken:

- We employed the most recent data included in the database Ecoinvent version 3.4 [42] that was released on the 4th October 2017 (high data quality).
- We employed data characterizing the European context in most cases (denominated with RER shortcut in the database); when it was not possible, we used activities and processes referred to Switzerland geographical location and indicated with the CH shortcut in the database. In few cases we were able to integrate directly data from EPD with high geographical correlation. While medium data quality could generally be obtained, a high data quality is guaranteed for the electricity production since the Italian national energy mix has been considered.
- We employed the most representative technology included in the Ecoinvent database. It has been possible to obtained very detailed information and technical sheets about the materials and systems installed in the buildings. In some cases, it has been possible to integrate the information contained in the EPD within the analysis (high technological correlation). When the EPD was not found, particular attention was paid to the thermal properties, to the mass density, to the mechanical properties, to the typology and of the materials installed in the construction. A high data quality has been reached for the insulation materials and PV systems while a medium data quality for all the other materials.

The Life Cycle Inventory includes a detailed list of all inputs and outputs in term of materials or energy at each stage of the life cycle of the building. The compilation of the LCI is based on the process analysis that is a bottom-up approach: the architectural, structural and equipment drawings were available with a high level of completeness. The Life Cycle Impact Assessment quantifies, from the inputs of the LCI, the numerical indicators of impact. Since the goal of the analysis is to determine the energy and carbon impacts linked to the building life cycle, the indicators that were chosen are the IPCC 2007 GWP 100a v1.03 [43] and Cumulative Energy Demand v1.09 [44], implemented in SimaPro software [45].

After performing a traditional LCA, we developed a dynamic calculation method able to describe firstly the sensitivity to some decarbonisation scenarios and then the effects of the temporary mismatch between load and PV generation on monthly and hourly basis.

The methodology used in this paper for the quantification of the carbon intensity includes the GHG emissions from the production and distribution of electricity (see Fig. 2). Literature studies [46,47] demonstrated that the embodied emissions are significant for renewable energy technologies while operational and upstream GHG emissions are largely prevailing in non-renewable power plants.

For this reason, the emissions spread for the construction, maintenance and decommissioning of electrical thermoelectric power plants, production facilities and distribution grids are not taken into account. On the contrary, the embodied emissions of renewable energy power plants are included through LCA emission factors. Furthermore, also the impacts linked to water use, acidification and pollutants emissions are not quantified. The assumptions for the calculation of the carbon emissions are deployed below:

- Reference year: 2015
- Geographic boundary: Italy and EU countries with which exchanges electricity (Switzerland, France, Slovenia, Austria, Greece).
- Greenhouse gas emissions: Italian gross electricity production emissions factors (ISPRA [48]), Italian national electricity balance (TERNA [49]), foreign carbon intensities [50–52].
- Upstream emissions are considered.
- Pumping and self-consumption of the production facility are included.
- Power losses: 10,4% losses in grids for LV electricity [53].

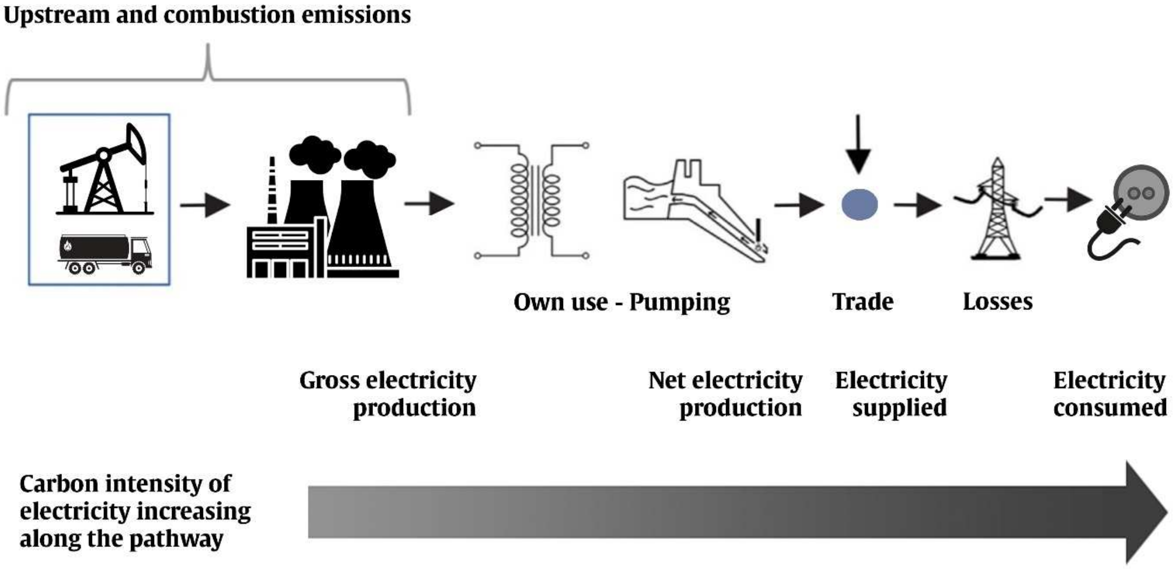


**Fig. 2.** Carbon intensity along the electricity pathway.

The carbon intensity is calculated as the ratio between the total greenhouse gas emissions ($GHG_{tot}$) spread for the production of a 1 kWh of LV electricity:

$$CI = GHG_{tot} / \text{El. Consumed LV} \tag{1}$$

Different values of the carbon intensity of a country are available for different electricity sources (see Fig. 2). The variation between the values provided is strongly dependent on the assumptions made during the calculations: emission factors adopted, national electricity mix, pumping and self-consumptions in production sites inclusion, consideration of energy imported from other countries, grid power losses,… In this paper we considered the emission linked to the consumption of an unity of low voltage electricity (220V). In Italy buildings are fed at low voltage that is also consumed by most of the users. The following equations (2), (3), (4), (5) display the calculations performed.

$$\text{El. Supplied to the grid} = TE + REP - \text{Self-C} + NFE \tag{2}$$

where TE is the thermoelectric production, REP is the renewable energy production (considering photovoltaic, wind, hydroelectric and geothermal), Self-C is the amount of energy consumed at the production sites, NFE (Net Foreign Exchange) is the difference between imported and exported energy. The related emissions are determined as the sum of operational ($GHG_{op}$) and upstream emissions ($GHG_{up}$):

$$GHG_{tot}= GHG_{op} + GHG_{up} \tag{3}$$

$$GHG_{op} = TE *EF_{t} + REP\ EF_{rep} + NFE * EF_{NFE} + Self\text{-}C\ EF_{m} \tag{4}$$

where $EF_t$, $EF_{ren}$, $EF_{NFE}$ and $EF_m$ are respectively the emission factors for thermoelectric production, renewable production, imported energy and self-consumption. The $EF_m$ is considered the average Italian emission factor for electricity production. The emission factor for NFE is determined as the average of the national carbon intensities of foreign countries weighted by their related exchanged amount.

$$\mathrm{EF}_{\mathrm{NFE}} = \frac{\sum_i NFE_i * CI_i}{NFE} \tag{5}$$

Static values are considered for all countries except for Switzerland because literature studies [52] demonstrated a sensible season variation of the carbon intensities for electricity production and because Switzerland is the principal import country of Italian electricity. Monthly values are used for Switzerland and derived from [52]. The 2015 mix of the country is mainly based on hydroelectric power (about 62%), nuclear power (about 30%) and residually on conventional thermal power plants fed by non-renewable energy sources. There are sensible seasonal variations in the electricity generation mix principally linked to the higher production of hydro power plants in summer. For that reason, a monthly emission factor was considered for the calculations with values ranging from 42 (in June and May) to 140 $gCO_2eq/kWh$ (in November and December).

France is the second country for electricity import. In France, during 2015, the main primary energy source for electricity generation was nuclear power (above 50% of the production). No significant seasonal variations are found about the carbon intensity of France [51]: the value considered is equal to 93 $gCO_2eq/kWh$ [50].

For Slovenian electricity imports, seasonal variations are exclude since the low incidence on total importations and a value of 361 $gCO_2eq/kWh$ is employed [50].

The contribution of Greek electricity in the influence of Italian carbon intensity is considered negligible since Italy exports electricity to Greece on annual basis [49].

The upstream emissions arise for the necessity to extract and deliver energy resources to the power stations: they include the GHGs for extraction, refining, transportations, as well as methane leakages from coal mining activities and natural gas pipelines. It was shown that the upstream GHG emissions can account for more than the 25% of the direct emissions of a fossil fuelled power plant [54]. The inclusion of upstream emissions is therefore important for non-renewable fuels while for renewable fuels, such as municipal and industrial wastes, hydropower, geothermal, solar and wind, the upstream stage can be neglected [50]. Table 3 and Table 4 reports the upstream and total emission factors adopted.

**Table 3.** Upstream emission factors adopted.

| **Fuel** | **Upstream emission factor ($gCO_2eq/kWh$)** |
|---|---|
| Natural gas | 46,1 |
| Petroleum products | 38,5 |
| Hard coal | 57,6 |
| Brown coal | 6,1 |

**Table 4.** Emission factors adopted.

| | **Emission factor ($gCO_2eq/kWh$)** |
|---|---|
| Traditional thermo-electric | 598 |
| Self-consumption | 465 |

| | |
|---|---|
| PV | 40 |
| Geothermal | 50 |
| Wind | 10 |
| Hydro | 24 |
| Net foreign exchange | 133 (variable form 104 to 155) |
| *Switzerland (51%)* | *98 (variable form 42 to 140)* |
| *France (32%)* | *93* |
| *Slovenia (13%)* | *361* |
| *Austria (4%)* | *170* |
| *Greece (-)* | *-* |

### *2.1 Stationary modelling (Method 1)*

Method 1 is introduced by equation (6): self-consumption is considered in this model employing a reduction factor of the final energy requirement of the building that is dependent on the Load Match Index (LMI). The LMI is the averaged value of the ratio between the PV generation and the building energy requirement: it is equal to 1 when the PV production is greater than the energy demand while it is 0 when there is no matching. The value of the LMI is strongly dependent on the grouping time frame used for its determination: longer time frames imply higher values of the LMI. In this work the LMI was determined on hourly basis and this makes the method not completely static. The GHG emissions with the static method are calculated using the following equation:

$$\mathrm{GHG}_{\mathrm{st}} = \sum\nolimits_{y} Fe\ (1 - LMI)\ CI(y) \tag{6}$$

with Fe (Final energy) equal to the final energy demand of the building (sum of energy consumptions for heating, cooling and lighting during one year) and y equal to the life span of the building (50 years).

Both symmetrical weighting and asymmetrical weighting between exported and imported energy are employed for the calculation of the NZEB balance. Symmetrical weighting extends the boundaries of the analysis to the grid including the benefits for avoided fossil fuels exploitation while the latter excludes this hypothesis and calculates locally the energy and carbon balance. Table 5 reports the current primary energy and emission (CI) conversion factors used.

**Table 5.** Conversion factors for the conversion of final (f) energy to primary (p) and emissions.

| | **Energy conversion factor** | **Carbon intensity** |
|---|---|---|
| ***Symmetrical weighting*** | | |
| Imported energy | 2.5 $kWh_p/kWh_f$ | 449 $gCO_2/kWh$ |
| Exported energy | -2.5 $kWh_p/kWh_f$ | -449 $gCO_2/kWh$ |
| ***Asymmetrical weighting*** | | |
| Imported energy | 2.5 $kWh_p/kWh_f$ | 449 $gCO_2/kWh$ |
| Exported energy | 1 $kWh_p/kWh_f$ | 0 $gCO_2/kWh$ |

#### *2.1.1 Decarbonisation inclusion*

Method 1 was applied with an annual grouping time frame to check the sensitivity to some decarbonisation scenarios. The expected values of the Carbon Intensity (CI) for electricity production depend on the future electricity mix of the countries and on their efforts in the decarbonisation of energy uses. The following equation (7) can be used to predict the electricity carbon intensity for every year [55]:

$$CI = \sum\nolimits_{j=1}^{k} PC_j \cdot EF_j \tag{7}$$

where PC is the percentage of the energy vector j in the electricity energy mix and $EF_j$ is the correspondent emission factor in $gCO_2eq/kWh$.

The International Energy Agency has provided some long term energy projections based on a World Energy Model (WEM) able to give different World Energy Outlook (WEO) scenarios [56]. The main scenarios developed in this study are:

- The Current Policy Scenario (CPS) or "Base Scenario" for the Italian National Energy Strategy (SEN 2017 [57]) takes into consideration only those policies that had been formally adopted since mid-2017 and that would permit, in 2030, to reach the 41,7% of REP;
- The New Policy Scenario (NPS) includes the intentions that had been announced since mid-2017 (including Paris Agreement) and will bring to the 55% of REP in 2030;
- The Sustainable Development Scenario (SDS) that addresses climate change in line with the goals of the Paris Agreement. The SDP considers an 85% of REP in 2050.

Using equation (7), two curves can be drawn plotting the emission factor in function of time: the first one (coloured in blue in Fig. 3) represents the time evolution of the emission factor with the current policy scenario (CPS) developed until 2030; the red curve of Fig. 3, instead, models the future electricity CI considering a new policy scenario (NPS) working until 2030 and a boost of the policy efforts for decarbonisation with the sustainable policy scenario (SDS) until 2050. The value of the CI is considered to remain stable at the level of 2030 and 2050 respectively for the CPS and SDS.

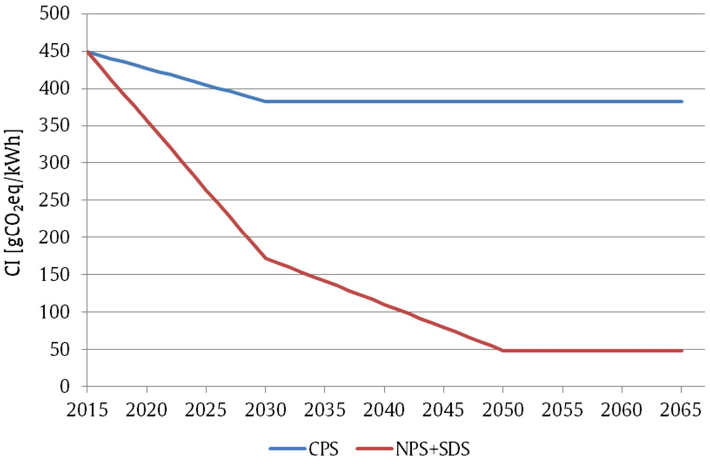


**Fig. 3.** Supposed linear evolution of the Italian CI (blue CPS, red NPS-SDS) for LV electricity.

### *2.2 Dynamic modelling (Method 2)*

Model 2 considers the self-consumption as shown by equation (8):

$$\text{Load}(t) = \text{Consumption}(t) - \text{PV production}(t) \tag{8}$$

Negative values mean an excessive electricity production that is put in the national grid and that is taken into account with a null emission factor. Positive values mean electricity imports from the grid that are multiplied for the right carbon intensity of the grid for the calculation of the global emissions as shown in equations (9).

$$\text{GHG} = \sum_t Load(t) * CI(t); \tag{9}$$

where t represents the grouping time frame (annual, monthly or hourly). In this paper three variants of Method 2 are considered:

- Method 2.1, called Dynamic Method, employs hourly values for the energy balance calculations and for CI;
- Method 2.2, called Mixed Method, uses hourly values for the energy modelling (load calculation) and an annual averaged value for the CI;
- Method 2.3, called semi-stationary method, considers a monthly aggregation for energy balance and CI values.

For every variant of Method 2 two versions were developed considering the symmetrical and asymmetrical conversion factors of Table 5.

## 3. Case study

### *3.1 Description of the case study*

The case study is a new prototype building located in Trento province in Italy and used as an exhibition space (see Fig. 4). The building has two levels connected by an internal timber staircase. Table 6 lists the main features of the building and of its location.

**Table 6.** Features of the building and of the location.

| **Building features** | |
|---|---|
| Number of floors | 2 |
| Structure | Glulam beam and columns |
| Walls | High insulated, light wooden frame |
| Roof | Wooden frame aerated and high insulated |
| Gross area | 110 $m^2$ |
| Gross internal area | 89 $m^2$ |
| Gross heated volume | 345.20 $m^3$ |
| Shape factor (1/m) | 1.04 |
| Windows to wall ratio (%) | 8.1% |
| **Building energy properties** | |
| Walls U-value | 0.117 $W/(m^2K)$ |
| Windows U-value | 0.910 $W/(m^2K)$ |
| Roof U-value | 0.149 $W/(m^2K)$ |
| Ground floor U-value | 0.132 $W/(m^2K)$ |
| COP heat pump | 4.54 |
| EER heat pump | 3.03 |
| Heat storage | 50 litres |
| **Location characteristics** | |
| City | Trento |
| Altitude | 195 |
| Latitude and Longitude | 45.8839 N and 11.0224 E |
| Heating degree days | 2713 |
| Climatic zone | E |
| Conventional heating period | from 15th October to 15th April |
| Solar radiation on horizontal surface | 1351 kWh $m^{-2}$ |

The ground floor level is 60 cm over the terrain level and the building has a foundation characterized by inverted beams that are directly at contact with the soil level. The external walls are highly insulated with four layers of insulation materials: 10 cm layer of high density mineral wool as a coating, a 5 cm layer of low-density mineral wool in the inner part of the wall, a 6.5 cm sandwich Laminate Veneer Lumber panel with high density mineral wool and a layer of 10 cm low-density mineral wool filled in the space between the wood columns. The resulting U-value of the external wall is 0.117 $W/(m^2K)$. Also, the roof is highly insulated with a triple layer of high density mineral wool located over the structural wooden layer. An air cavity of 5.4 cm guarantees the ventilation of the roof that is covered with a metal sheet. The U-value is equal to 0.149 $W/(m^2K)$. The inter-floor ceiling is insulated with a 6 cm layer of low density rock wool and an additional 3 cm insulation panel of wood fibre characterizing the underfloor heating system; the calculated U-value is equal to 0.235 W/(m$^2$K). Further 16 cm of low density rock wool are added in the ground level floor that has a U-value of 0.132 W/(m$^2$K). High performance windows are installed in the building: the U-value of the transparent part (triple 4-14-4-14-6 glazing with Argon filling) is 0.60 W/(m$^2$K), a warm edge spacer is installed between the glass sheets and softwood frame is mounted. The global U-value of the windows is 0.91 W/(m$^2$K) while the French window at the entrance is characterized by a lower value of 0.89 W/(m$^2$K) . All the U-values cited are much lower than the limits about thermal transmittance of the envelope that will be mandatory in Italy from 2019 for climatic zone E [58].

The heating system of the building is composed by an air-to-water heat pump and a screed free radiant underfloor distribution system, integrated in the floors and working at a temperature of 35°C. In summer the heat pump works in inverse cycle and the distribution system is characterized by fan coils. The technical sheet of the installed heat pump reports a related COP$_{7\text{-}35}$ of 4.54 and a related EER$_{35\text{-}7}$ equal to 3.03 measured at the full load and at the compressor rating frequency. Two distribution manifolds control the flow in the circuits for heating and cooling. The high performance variable speed pump installed absorbs a power of 40W for flows over 1 m$^3$/h. A 50 liters storage tank is directly connected to the heat pump with the purpose of reducing the number of on-off cycles of the system. The heat pump is oversized for the building's energy needs, as often happens in real buildings in order to provide for domestic hot water requirements. The frequent operation at a low capacity ratio induces a high COP degradation of the heat pump.

The electric energy consumption of the heat pump is partially covered by the PV system. Fourteen multi-Si panels are installed with a total PV surface of about 23 m$^2$ and a total peak power of 3.5 kW. Table 7 reports all the materials included in the LCI obtained from the executive project of the building chosen as case study: very refined data were available about the typologies, properties and characteristics of the materials that are included in the building.

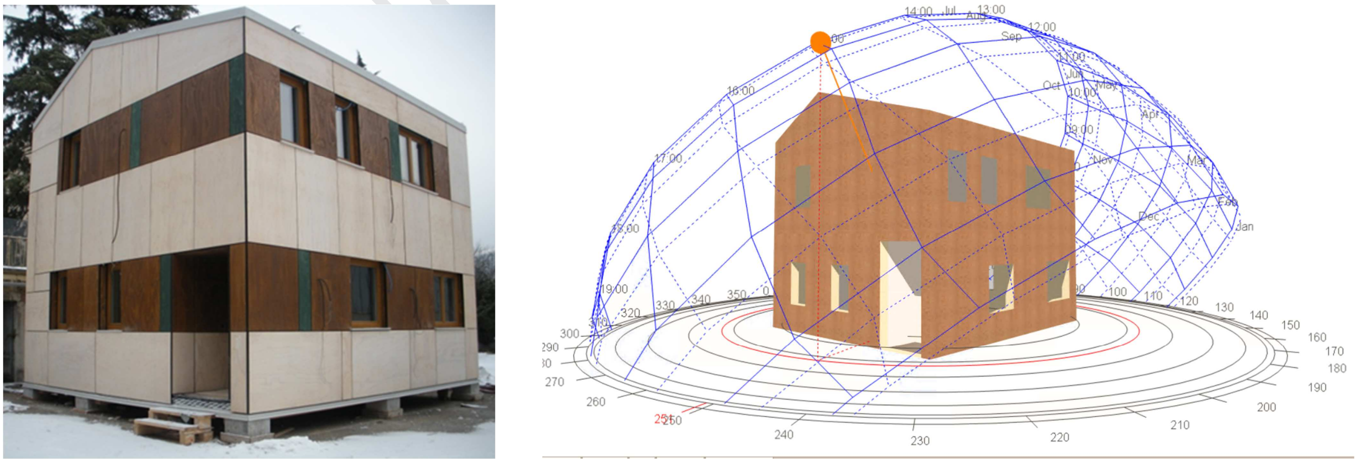


**Fig. 4.** Picture and Sketch of the building.

**Table 7.** Main materials and systems included in the analysis.

| | **Component** | **Materials** | **Quantities** |
|---|---|---|---|
| ***Load bearing structure*** | Foundation | Concrete, normal | 4200 kg |
| | | Reinforcing steel (4%) | 550 kg |
| | | Poor concrete | 5145 kg |
| | Structure (load bearing) | Glulam | 4800 kg |
| | | Steel, connections | 2112 kg |
| | Stairs | Concrete, normal | 4240 kg |
| | | Reinforcing steel (4%) | 530 kg |

| | | | |
|---|---|---|---|
| ***Horizontal subdivisions*** | Floors | Laminate flooring | 100 $m^2$ |
| | | Cross laminated timber (500 kg/$m^3$) | 4000 kg |
| | | Wood fibre insulation | 1254 kg |
| | | Plywood (530 kg/$m^3$) | 1150 kg |
| | | Rockwool (40 kg/$m^3$) | 240 kg |
| ***Envelope*** | Vertical walls | Mineral wool (40 kg/$m^3$) | 1600 kg |
| | | Mineral wool (135 kg/$m^3$) | 2820 kg |
| | | Insulated LVL panel | 2770 kg |
| | | Polyethylene vapour brake | 210 $m^2$ |
| | | Gypsum boards | 4700 kg |
| | | Steel profiles | 210 kg |
| | | Concrete panel, prefabricated | 7520 kg |
| | | Wooden studs | 414 kg |
| | | Water | 39 l |
| | | Gypsum plaster | 234 kg |
| | | Wall paint | 39 l |
| | | Softwood window frame | 17 $m^2$ |
| | | Flat glass, windows | 17 $m^2$ |
| | | Argon | 0.14 $m^3$ |
| | | Warm spacer, silicone | - |
| | Roof | Mineral wool (135 kg/$m^3$) | 1769 kg |
| | | Laminated timber | 1445 kg |
| | | Bitumen coating | 68 $m^2$ |
| | | Steel sheet, galvanized | 68 $m^2$ |
| ***Vertical subdivisions*** | Internal walls | Gypsum board | 4500 kg |
| | | Laminated timber | 250 kg |
| | | Steel connections | 30 kg |
| | | Water | 10 l |
| | | Gypsum plaster | 60 kg |
| | | Wall paint | 10 l |
| ***Systems*** | Generator | Heat Pump | 7 kW |
| | | Hot water tank | 50 l |
| | Distribution system | Pump | 40 W |
| | | Copper pipes | 15 kg |
| | | Polymeric material pipe | 65 kg |
| | | Polyurethane Insulation | 0.5 kg |
| | | Valves-Manifolds (brass) | 40 kg |
| | | Fan coils | 3 |
| | Lighting | LED lamps (8 W) | 6 |
| | PV | Multi-crystalline panels with frame | 23 $m^2$ |
| | | Inverter | 3,5 kW |
| | | Electric installation (3 kW) | 1 |
| | Transports | Pick-up truck | 60 km |
| | | 32 tonnes truck | 60 km |

### *3.2 Energy monitoring*

The monitoring campaign focused on the energy demand and on the parameters describing the HVAC systems and the building envelope. All the variables were registered continuously every 5 minutes from January 2015 to December 2015.

Although limited to a single year, the measures are sufficiently representative of the multi-year period. The average dry bulb temperature and the average daily global solar radiation collected in 2015 show deviations of 7% and 2% compared to the typical reference year (TRY) computed for the site. The representativeness of the latter was already tested in previous works [59,60], which demonstrated its ability to capture the long-term trend.

Internal temperature and relative humidity were collected in all the rooms, using a resistance thermometer PT100 and a capacitive hygrometer having an accuracy of ±0.5 K for the temperature measurement and of

± 5% for the humidity measurement. Similarly, the same temperature and humidity probes were installed to collect the temperature and relative humidity of the external environment.

Moreover, the south facing wall and the roof were equipped with heat flow meters and temperature probes positioned on the surfaces and on the internal layers in order to register the envelope performances. The probes and the data acquisition chain accuracy is identified as 0.5°C for the thermocouples placed on the internal layers and 0.3°C for the Platinum Thermo-Resistances on the internal and external surfaces of the opaque components. The accuracy of the heat flux meters is ±3% at 100 $W/m^2$.

The HVAC system worked continuously with a heating setpoint of 20 °C during the heating season (Table 6) and a cooling setpoint of 26 ° C in the remaining part of the year.

The energy delivered to each loop of the radiant floor was measured using a "Sauter F2HC" energy meter. The power production of the PV system, including the inverter losses, and the power absorption of the HVAC systems were measured by two "ABB OD1065" energy meters having an accuracy of ±5% of the readings. All monitoring data were sent through KNX and BACnet protocols to the PC-based data acquisition system and logged every 5 minutes.

Fig. 5 shows the trends in PV production and energy consumptions measured during the experimental test. Lighting consumptions are negligible since there were no occupants in the experimental building. Hence, the total energy consumption is the sum of the electricity absorbed by the heat pump and the auxiliary systems during the heating and cooling seasons and it is lower than the on-site renewable energy of the PV.

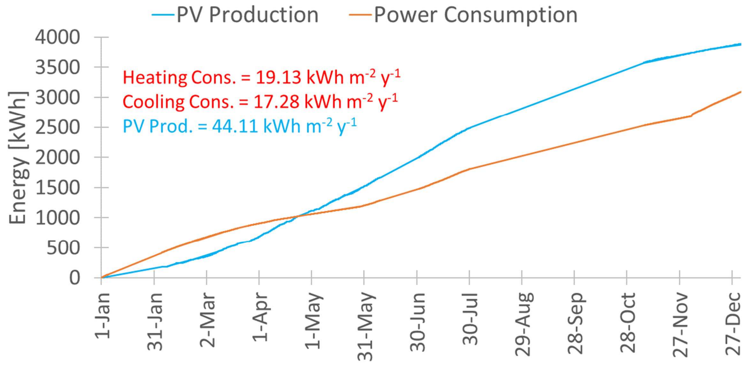


**Fig. 5.** Measured annual energy consumption and PV production.

A sensible mismatch between PV production and power consumption was detected for the monitored building. This aspect is highlighted by the typical trends shown in Fig. 6a for some winter, 6b summer and 6c intermediate periods, for which the hourly match indexes are 26%, 52% and 42% respectively. The availability of one year monitoring data about consumption and PV generation, with time frequency of ten minutes, allowed to determine the load match index. The hourly value is equal to 40.5%. Storage batteries can be installed in the building or advanced heat pump management logics can be designed [61] in order to increase self-consumption; however these systems are not considered within this paper.

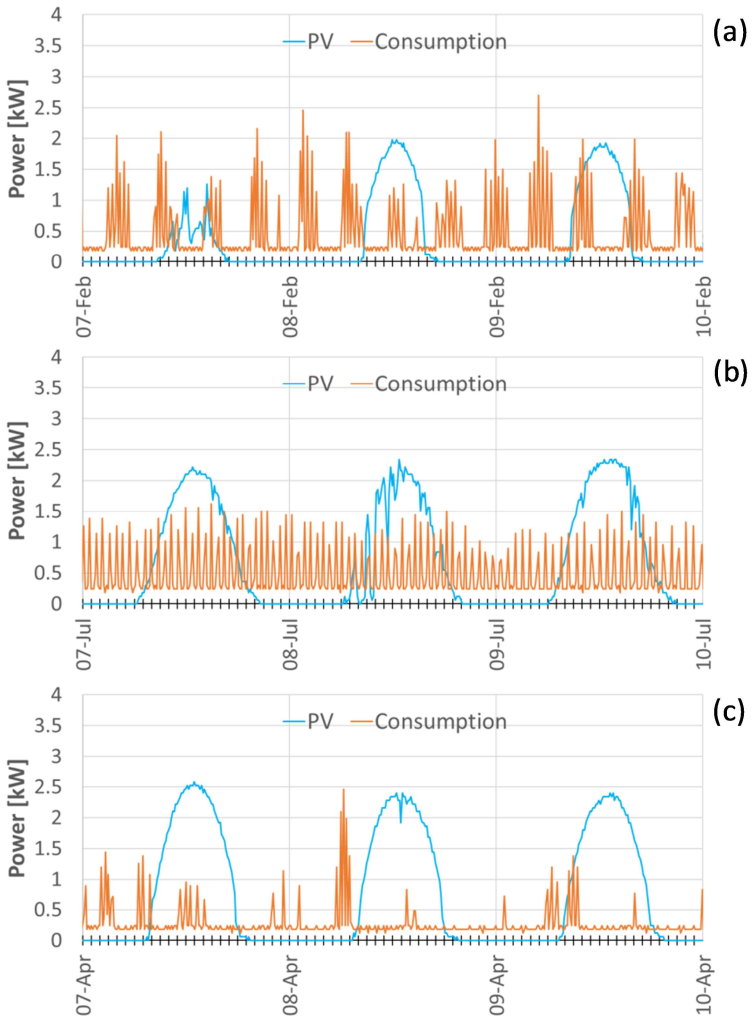


**Fig. 6.** Typical mismatch trends for winter (a), summer (b) and intermediate periods (c).

## 4. Results and discussion

### *4.1 LCA with stationary energy modelling*

Table 8 shows the EE and EC of the building elements and plants components. The vertical walls and the PV system are energy and carbon hot spots because they together account for an important percentage of the total embodied impacts of the construction (respectively 42% and 57% for the embodied energy and carbon as can be noted from Fig. 7-8). The roof has a high embodied energy due to the presence of the galvanized steel coverage. The embodied energy and carbon of the wooden load bearing structure is mainly linked to the use of steel connections: glulam has a low embodied energy and a negative embodied carbon. The negative embodied carbon of floor component is linked to the large use of wood in their construction. It is interesting to note that the embodied energy of the HVAC is about half of the one regarding building elements.

**Table 8.** Embodied Energy and Carbon for every building component.

| **Component** | **Embodied Energy (kWh)** | **Embodied Carbon (kgCO$_2$eq)** |
|---|---:|---:|
| Foundation | 5 906 | 2 154 |
| Stairs | 2 724 | 881 |
| Structure | 90 728 | 3 524 |
| Floors | 64 984 | -2 741 |
| Vertical walls | 136 805 | 18 307 |

| | | |
|---|---:|---:|
| Roof | 80 576 | 9 105 |
| Internal walls | 6 135 | 587 |
| Heating/lighting equipment | 37 625 | 9 301 |
| PV system | 86 143 | 16 937 |
| Transports | 18 821 | 4 102 |

For the calculation of the recurring embodied carbon, the study assumes one or more replacements of the building components in function of their useful life. A variation of the energy performances of the building components (e.g. a reduction of the efficiency of the PV panels or of the insulation material deterioration) was not considered because these considerations go beyond the limits of the study.

The end-of-life energy includes the energy uses for controlled demolition, transportation to the landfill and recycling operations. The emitted carbon from wood elements burning was also taken into account.

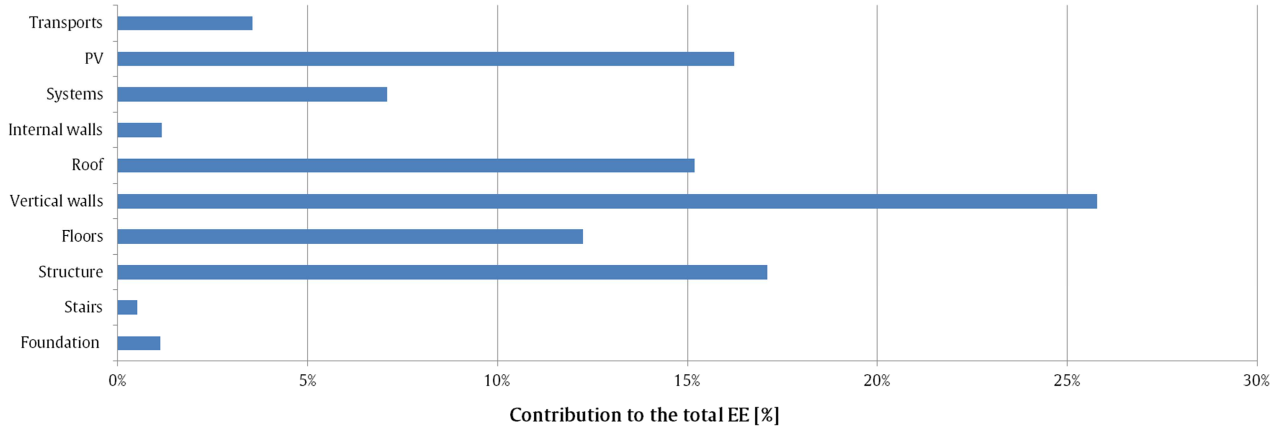


**Fig. 7.** Contribution of every building component to the embodied energy.

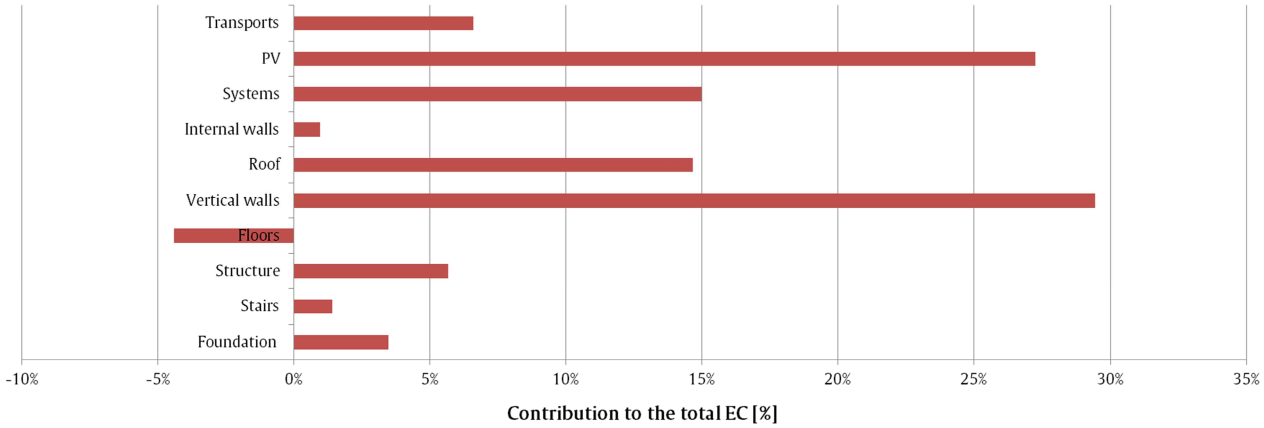


**Fig. 8.** Contribution of every building component to the embodied carbon.

The primary energy balance of the building was determined by monitoring the energy demand and PV production. Table 9 shows the energy balance of the building considering both final and primary energy balancing. Looking at the load-generation balance, the prototype chosen as a case study can be considered a Nearly Zero Energy Building (NZEB).

**Table 9.** Final and primary energy balance of the building.

| | **Final Energy (kWh/(m$^2$ y))** | **Primary Energy (kWh/(m$^2$ y))** |
|---|---|---|
| Heating | 19.13 | 47.82 |
| Cooling | 17.28 | 43.20 |
| Lighting | ≈ 0 | ≈ 0 |
| PV generation | 44.11 | 44.11 |

Table 10 and Fig. 9a-9b-10a-10b show the life cycle energy and carbon balance of the building.

**Table 10.** Life Cycle Energy and Carbon components.

| | CED (kWh/m$^2$ y) | GWP (kgCO$_2$eq/m$^2$ y) |
|---|---|---|
| Initial | 83 | 8.38 |
| Recurring | 36 | 5.59 |
| Consumption | 54 | 9.73 |
| Generation (symmetrical) | -73 | -13.15 |
| Generation (asymmetrical) | -28 | 0 |
| End-of-life | 6 | 8.16 |

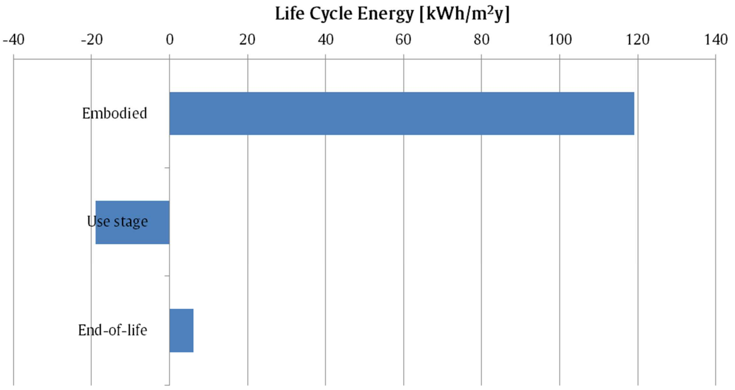


**Fig. 9a.** Life Cycle Energy balance (symmetrical weighting).

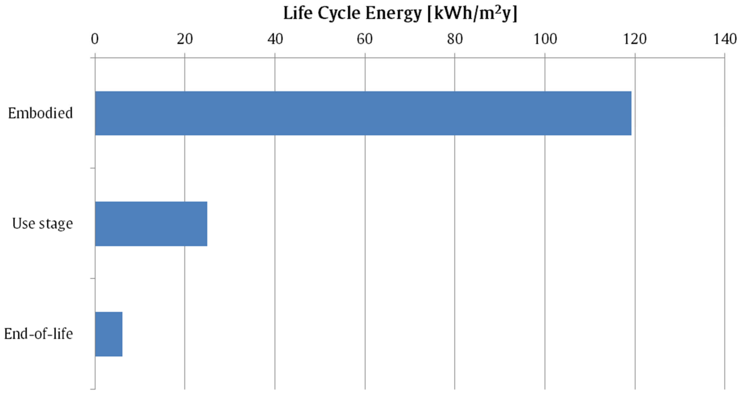


**Fig. 9b.** Life Cycle Energy balance (asymmetrical weighting).

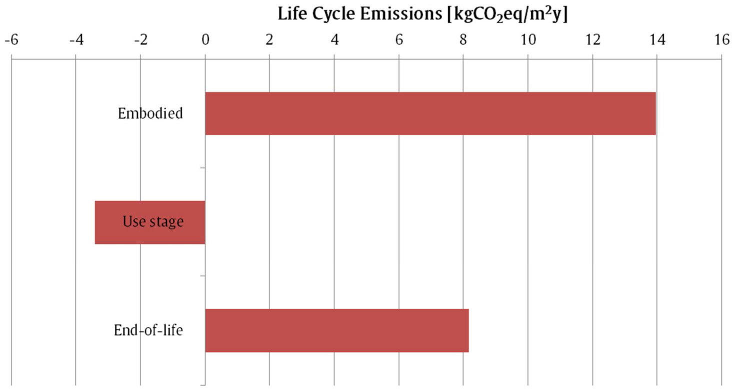


**Fig. 10a.** Life Cycle Carbon balance (symmetrical weighting).

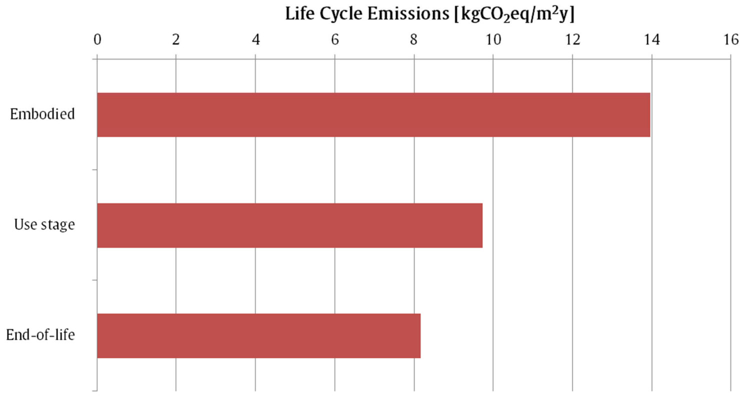


**Fig. 10b.** Life Cycle Carbon balance (asymmetrical weighting).

The contribution of the different life cycle stages is strongly dependent on the typology of weighting systems used as shown in Table 11.

**Table 11.** Incidence of the life cycle stages with symmetrical and asymmetrical conversion factors.

| | **CED embodied** | **CED use stage** | **CED EoL stage** |
|---|---|---|---|
| Symmetrical | 112% | -18% | 6% |
| Asymmetrical | 79% | 17% | 4% |
| | **GWP embodied** | **GWP use stage** | **GWP EoL stage** |
| Symmetrical | 75% | -18% | 43% |
| Asymmetrical | 44% | 31% | 25% |

### *4.1.2 Decarbonisation sensitivity*

The inclusion of decarbonisation in the analysis can play an important role. When fossil fuels substitution is considered, the decarbonisation brings to an increase of the total GWP of the building because lower savings can be obtainable during the operational stage (see Fig. 11a). The maximum increase is equal to -12% for NPS+SDS 2050 and the minimum is -2% when the CPS 2030 is considered.

On the contrary, when asymmetrical weighting is considered, the decarbonisation of the electricity will reduce the global life cycle emissions linked to the case study cutting the emissions linked to the supply of the electricity from the national grid (see Fig. 11b). The maximum annual reduction obtainable through the most challenging decarbonisation scenario is equal to -20% of the total life cycle emissions (about 569 kgCO$_2$-eq/y) in 2050 and -9% (about 267 kgCO$_2$-eq/y) in 2030; meanwhile the continuation of the current policies will produce a decrease of the building life cycle emissions per year of -4% in 2030 that corresponds to 108 kgCO$_2$-eq/y.

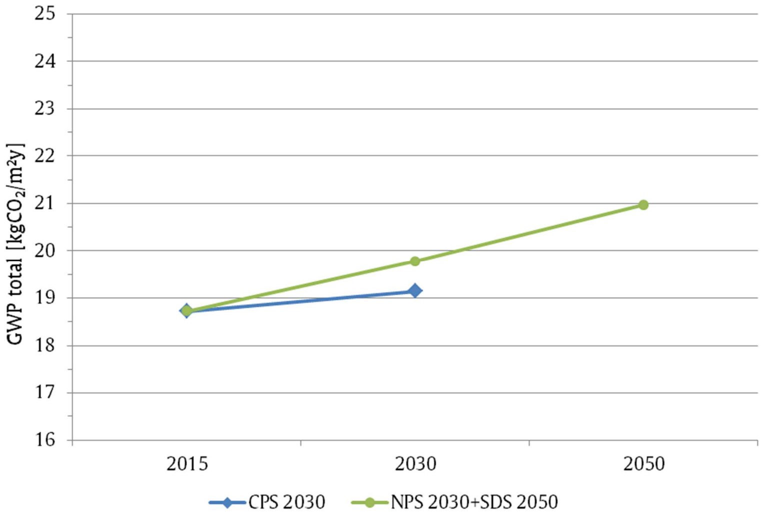


**Fig. 11a.** Total GWP of the building in different decarbonisation scenarios (symmetrical weighting).

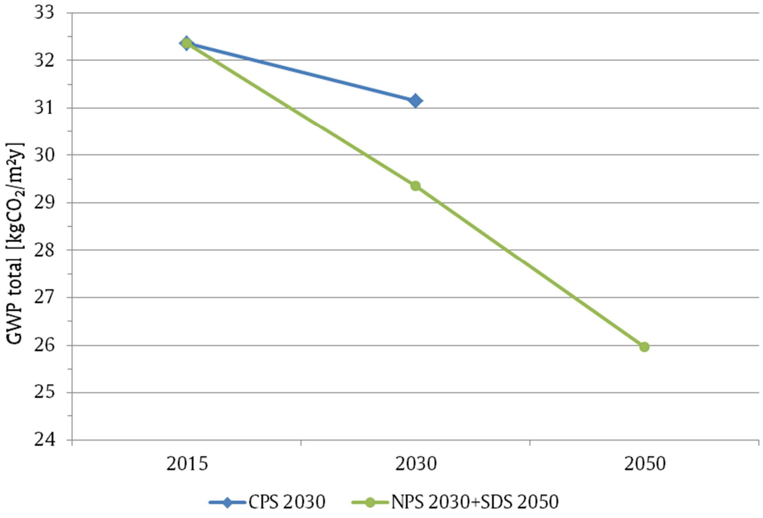


**Fig. 11b.** Total GWP of the building in different decarbonisation scenarios (asymmetrical weighting).

### *4.2 Sensitivity to different modelling methods*

The results obtained using Method 2 are dependent on the aggregation time frame employed. In fact, it should be noted that, the annual aggregation of data doesn't permit to describe adequately the real self-consumption amount: the PV system produces more energy than the annual requirement of the building so that the use of equation (8) for the calculation of the GHG emissions doesn't permit to capture any carbon emitted during the building operation. The use of Method 2 necessary requires tighter grouping time frames to estimate the GHG emission with a better accuracy. We so considered monthly values for load and PV generation implementing method 2.3 (see Table 12). The low energy consumption of the building is quite always covered by the PV production as can be seen from Fig. 12: the consumption is higher than the renewable energy production only during January, February, November and December.

**Table 12**. Load and generation values characterizing the case study.

| | Energy demand [kWh] | PV generation [kWh] |
|---|---|---|
| January | 369 | 164 |
| February | 283 | 195 |

| | | |
|---|---|---|
| March | 237 | 336 |
| April | 154 | 432 |
| May | 151 | 413 |
| June | 264 | 471 |
| July | 334 | 492 |
| August | 275 | 424 |
| September | 195 | 322 |
| October | 201 | 248 |
| November | 218 | 179 |
| December | 422 | 167 |

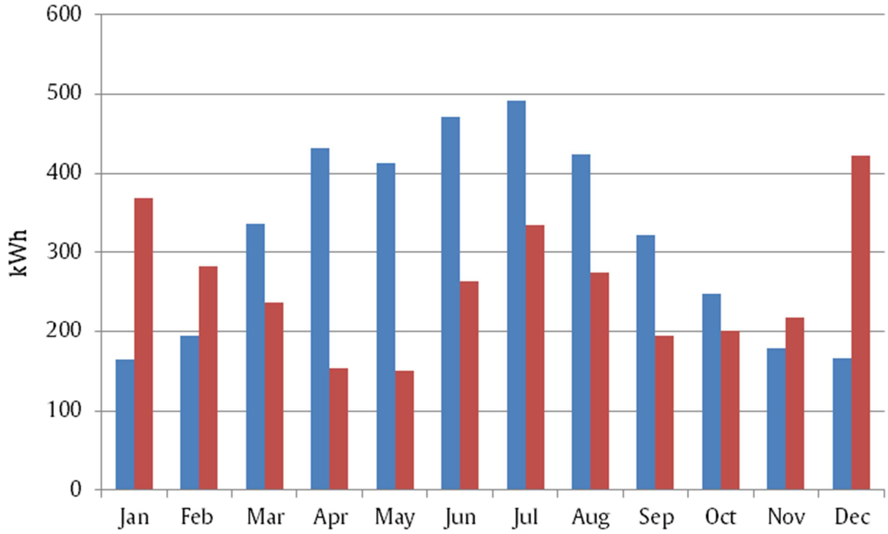


**Fig. 12.** Monthly PV production and consumptions of the case study.

After the reconstruction of the monthly load-generation profile of the building, the monthly carbon intensity profile was drawn (see Fig. 13 and Table 13) using the methodology already introduced. The profile is referred to 2015 and it is obtained starting from hourly data of the energy mix published by TERNA [49]. It should be noted that during the summer months (July, August and September), when there is the maximum availability of solar irradiance, the carbon intensity of the electricity produced in Italy is characterized by high values that are similar to the ones obtained in January and February.

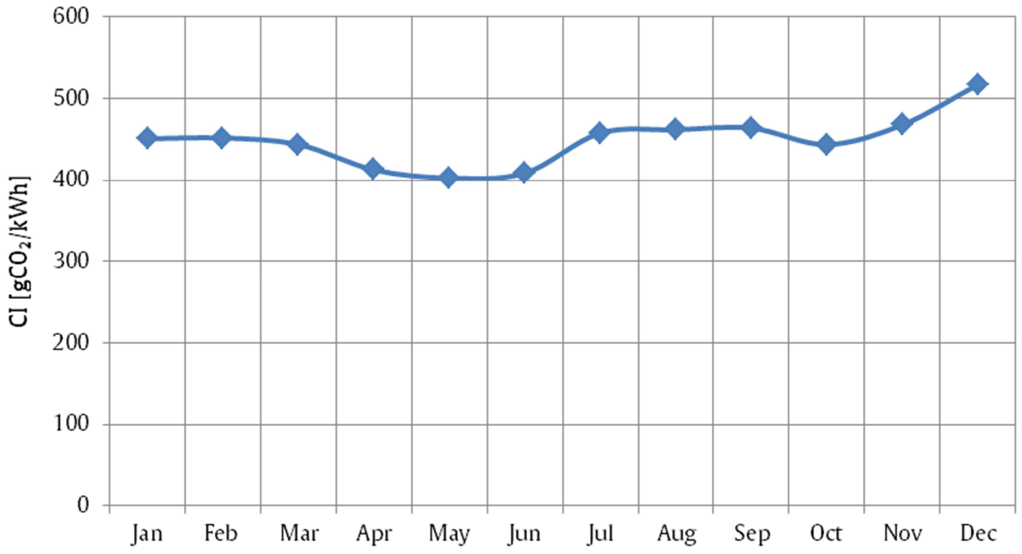


**Fig. 13.** Monthly carbon intensity for low voltage electricity in Italy (2015).

**Table 13**. Values of the monthly and annual averaged carbon intensity used.

| | Carbon Intensity [gCO$_2$/kWh] | |
|---|---|---|
| | *Monthly value* | *Annual average* |
| January | 451 | 449 |
| February | 452 | 449 |
| March | 444 | 449 |
| April | 413 | 449 |
| May | 403 | 449 |
| June | 409 | 449 |
| July | 458 | 449 |
| August | 462 | 449 |
| September | 464 | 449 |
| October | 444 | 449 |
| November | 468 | 449 |
| December | 517 | 449 |

Dynamic hourly simulations (method 2.1) were then performed in order to compare the results with the monthly outputs of method 2.3 and with the outputs obtained using a dynamic energy modelling and a static annual value of the CI (method 2.2).

As reported in Fig. 14a - 14b, the different modelling methodologies give a different value of the total annual carbon emissions of the case study. The variation in the results can be significant: methods 2.3 and 2.2 tend to underestimate the total emissions for unsymmetrical weighting and to overestimate benefits for symmetrical weighting.

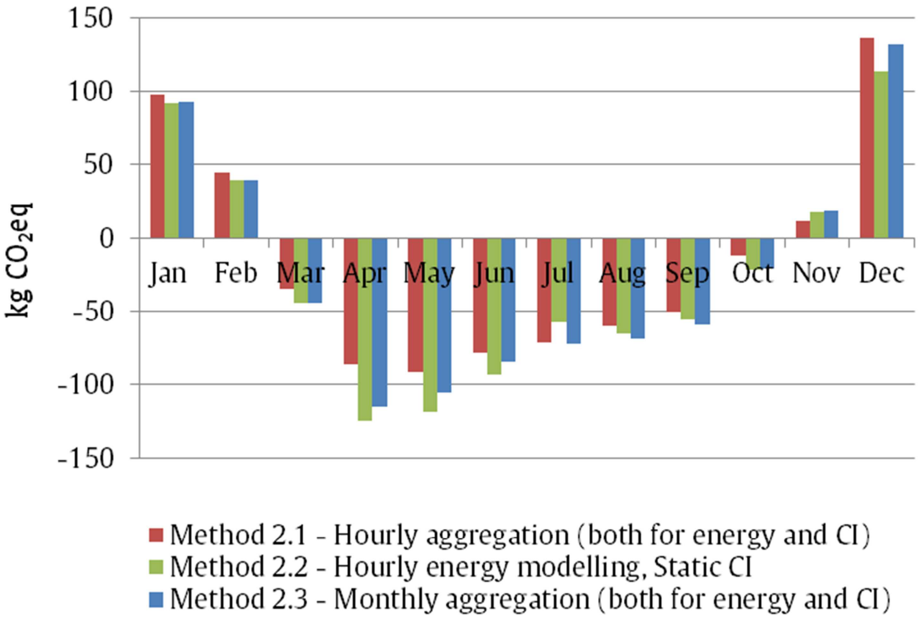


**Fig. 14a.** Carbon emissions every month with different variants of Method 2 (symmetrical weighting).

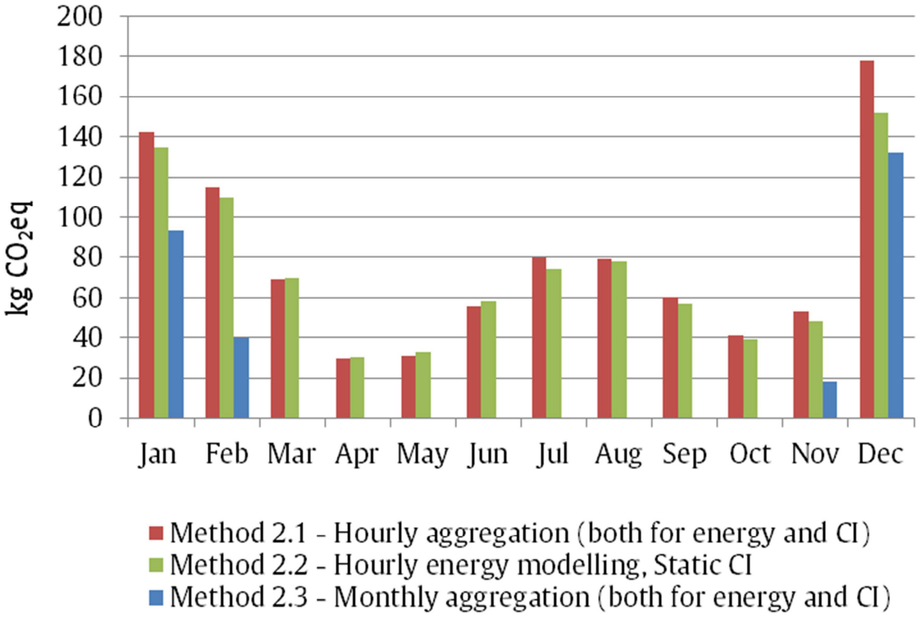


**Fig. 14b.** Carbon emissions every month with different variants of Method 2 (asymmetrical weighting).

Three significant months (December, July and May) were chosen for a more detailed discussion. Fig. 15-16-17 report the hourly load of the case study and the related hourly carbon intensity employed for the determination of the GHG emissions during these three months.

The results obtained for December are the following:

- Global emissions dynamic method: 136 kg$CO_2$-eq (symmetrical weighting) -178 kg$CO_2$-eq (asymmetrical weighting)

- Global emissions mixed method: 114 kgCO$_2$-eq (symmetrical weighting) - 152 kgCO$_2$-eq (asymmetrical weighting)
- Global emissions semi-stationary method: 132 kgCO$_2$-eq

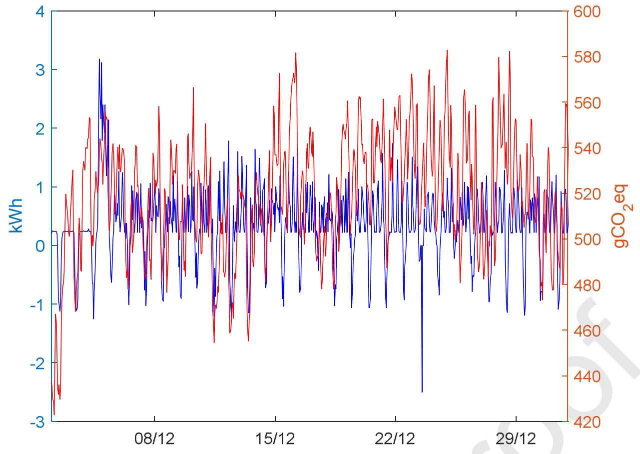


**Fig. 15.** Hourly load and carbon intensities in December.

For July we got the following results:

- Global emissions dynamic method: -71 kgCO$_2$-eq (symmetrical weighting) - 80 kgCO$_2$-eq (asymmetrical weighting)
- Global emissions mixed method: -57 kgCO$_2$-eq (symmetrical weighting) -74 kgCO$_2$-eq (asymmetrical weighting)
- Global emissions semi-stationary method: -72 kgCO$_2$-eq (symmetrical weighting) - 0 kgCO$_2$-eq (asymmetrical weighting)

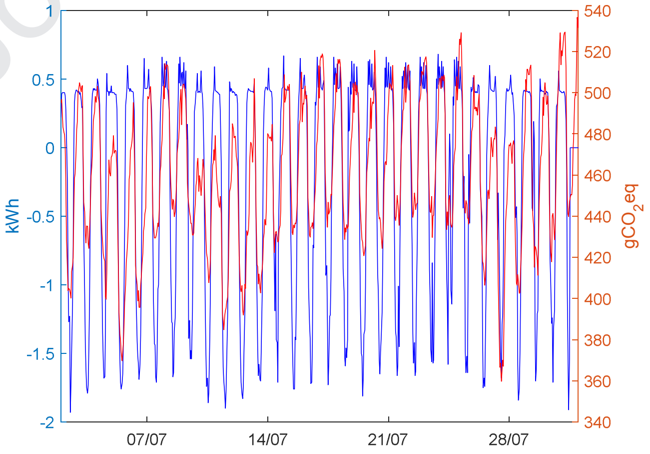


**Fig. 16.** Hourly load and carbon intensities in July.

The results obtained for May are reported as follows:

- Global emissions dynamic method: -91 kgCO$_2$-eq (symmetrical weighting) - 31.2 kgCO$_2$-eq (asymmetrical weighting)

- Global emissions mixed method: -118 $kgCO_2$-eq (symmetrical weighting) - 32.5 $kgCO_2$-eq (asymmetrical weighting)
- Global emissions semi-stationary method: -105 $kgCO_2$-eq (symmetrical weighting) - 0 $kgCO_2$-eq (asymmetrical weighting)

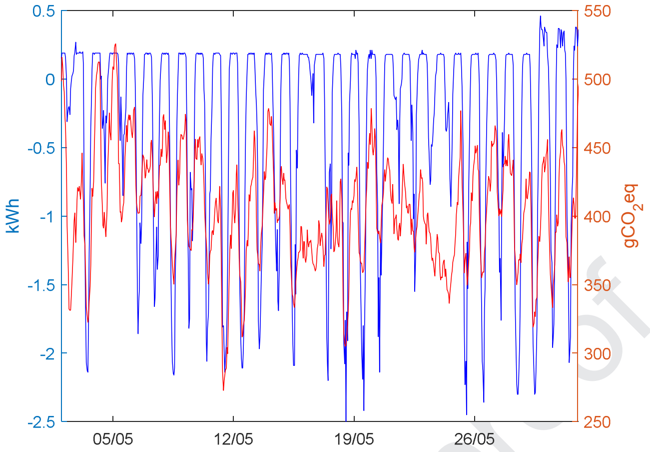


**Fig. 17.** Hourly load and carbon intensities in May.

Finally, it is possible to observe a not negligible underestimation of the total operational GHG emissions obtainable through Method 1 in case of asymmetrical weighting: Method 2.1 gives a value of the total operational emissions of 935 $kgCO_2eq$ while stationary modelling (Method 1) returns a value of about 867 $kgCO_2eq$ (-7%); in case of symmetrical weighting the overestimation of benefits of the stationary method is equal to 36% (-303 $kgCO_2eq$ against -192 $kgCO_2eq$).

The sensitivity of the modelling technique for operational carbon on the life cycle carbon of the building turns to be not negligible: the use of the completely dynamic modelling (Method 2.1) instead of the more traditional one (Method 1) brings to an increase of the life cycle emissions of 2.4% for asymmetrical weighting and of the 8% in case of symmetrical weighting.

### *4.3 Discussion about LCA of similar constructions*

At the end of the analysis, some literature references have been found and compared from the methodological point of view. All the buildings selected are located in Italy, are equipped with electrical heating and cooling systems and are very efficient constructions that usually integrate renewable energy systems.

The comparison of their LCA outputs shows a not negligible difference in the total environmental impacts and in the incidence of the single life cycle stages linked to the deep variations in the modelling techniques adopted, in the conversion factors employed, in the methodologies for the calculation of energy balances considered and in the end-of-life benefits inclusion (see Table 14).

**Table 14.** Main LCA assumptions for the similar case studies.

| | Life span years | Primary Energy Balance | Matching modelling | Conversion factors | End of Life Benefits | CI modelling |
|---|---|---|---|---|---|---|
| This case study | 50 | Import-Export | Hourly | Symmetrical – Asymmetrical | Excluded | Static - Dynamic |
| Prefabricated NZEB [62] | 25 | Import-Export | Sub-hourly | Asymmetrical | Excluded | - |
| Prefabricated NZEB [63] | 25 | Import-Export | Sub-hourly | Symmetrical | Excluded | Static |
| Plus Energy Module 1 [64] | 10 | Load-Generation | Annual | Symmetrical | Included | Static |

| | | | | | | |
|---|---|---|---|---|---|---|
| Plus Energy Module 2 [64] | 10 | Load-Generation | Annual | Symmetrical | Included | Static |
| Plus Energy Module 3 [64] | 10 | Load-Generation | Annual | Symmetrical | Included | Static |
| Leaf House [65] | 70 | Import-Export | Sub-hourly | Asymmetrical | Included | - |

All these assumptions, linked to the lack of a common standardized method, make the LCA results of quite similar case studies very divergent; after a homogenization attempt, that considers the benefits of exported electricity and of the EoL management outside the boundaries of the analysed system, we got the outputs about the CED reported in Table 15. A higher standardization of the methodology is however necessary for the definition of benchmarks.

**Table 15.** Life Cycle Energy results and comparison with similar case studies.

| | Area $m^2$ | Mean U-value *$W/m^2K$* | PV *$KW_p$* | CED (Embodied) *%* | CED (Use stage) *%* | CED (EoL) *%* | CED (Total) *$kWh/m^2$ year* |
|---|---|---|---|---|---|---|---|
| This case study | 89 | 0.13 | 3.5 | 67% | 30% | 3% | 179 |
| Prefabricated NZEB [62] | 45 | 0.39 | 3.5 | 68% | 27% | 5% | 256 |
| Prefabricated NZEB [63] | 45 | 0.39 | 5.8 | 88% | 7% | 5% | 196 |
| Plus Energy Module 1 [64] | 15.8 | 0.085 | 1.0 | 90% | 10% | ≈0% | 278 |
| Plus Energy Module 2 [64] | 15.8 | 0.085 | 1.0 | 85% | 15% | ≈0% | 174 |
| Plus Energy Module 3 [64] | 15.8 | 0.085 | 1.0 | 93% | 7% | ≈0% | 433 |
| Leaf House [65] | 610 | 0.23 | 20 | 77% | 23% | ≈0% | 163 |

## 5. Conclusions

The Dynamic Life Cycle Assessment faces the limitations of the traditional approach of a LCA trying to increase its robustness in the evaluation of the environmental performances of systems with a long file span, such as buildings. This study shows that the results can be sensitive to the assumptions made on some time dependent parameters (e.g. the CI and the matching between loads and PV generation) and on the conversion factors adopted for the calculation of the NZEB balance. Symmetric and asymmetric weighting was considered in the evaluations and it was found to highly influence LCA results and contributions of life cycle stages: some research is still needed to better understand how exported energy can be taken into account in buildings’ LCA.

Then, the sensitivity to a time variation of the carbon intensity for the electricity production is checked considering some decarbonisation scenarios. The maximum possible reduction of the life cycle emissions is equal to -20% for asymmetrical weighting and -12% for symmetrical weighting.

Finally, the paper analyses the sensitivity of the results about GHG emissions of the use of two different modelling techniques (stationary and dynamic), both able to capture the matching between loads and PV generation in different ways. The results are found to be very sensitive to the sampling period used for the calculations and a higher sampling frequency, both for energy and CI, is able to capture the operational emissions more accurately. In fact, the application of the dynamic Method 2.1 estimates an amount of life cycle emissions 8% higher when symmetrical weighting is employed. The smaller variation of the results obtained using asymmetrical weighting (e.g. 2.4%) could be linked to small seasonal variation of $CO_2$ emissions per kWh according to the Italian electricity mix. A high level of variation can be verified in other countries where the hourly and seasonal values of the CI fluctuate more. An hourly dynamic simulation is so strongly recommended for a higher reliability in results, even though some uncertainties remain. For example, about the decarbonisation scenarios, results are strongly dependent on the effective achievement of the targets set by the governments in the prescribed deadlines. Moreover, the introduction of dynamic parameters makes the methodology more complex and increases the difficulty of a comparison with other literature results for the definition of benchmarks. The Product Category Rules represent a good reference for the definition of a common methodology in the LCA of buildings or products, but they don’t consider the temporal dimension of building systems and doesn’t give any reference about how to consider benefits deriving from grid-exported renewable energy. An international homogenization in this field is recommended to obtain more reliable and comparable results that can represent a consistent database for the definition of environmental benchmarks in the construction sector.

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## HIGHLIGHTS

- DLCA is proposed to evaluate consequences of electricity decarbonisation on the LCA;
- Analysing the effect of different modelling techniques of future emission factors;
- A case study of an “all electric” building is introduced;
- Analysing electricity decarbonisation effects in the LCA of a low energy building.

**Declaration of interests**

☒ The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

☐The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: