Available online at www.sciencedirect.com

ScienceDirect

Energy Procedia 140 (2017) 486–494

Energy Procedia

www.elsevier.com/locate/procedia

AiCARR 50th International Congress; Beyond NZEB Buildings, 10-11 May 2017, Matera, Italy

Life cycle energy performances of a Net Zero Energy prefabricated building in Sicily

Giovanni Tumminia[a]*, Francesco Guarino[a], Sonia Longo[a], Marina Mistretta[b], Maurizio Cellura[a], Davide Aloisio[c], Vincenzo Antonucci[c]

[a]*DEIM Department, University of Palermo, Viale delle Scienze, Building 9, Palermo 90128, Italy*
[b]*PAU Department, University of Reggio Calabria, Salita Melissari Feo di Vito, Reggio Calabria I-89124, Italy*
[c]*Institute for Advanced Energy Technologies "Nicola Giordano", National Research Council of Italy, Via Salita S. Lucia sopra Contesse, Messina 98126, Italy*

Abstract

The paper presents the energy performances in a life cycle perspective of a prefabricated building. The building was simulated in energy plus and validated on monitored data. To avoid the shifting of energy burdens from one life cycle stage to others, a Life Cycle Energy Assessment was performed.

The primary energy use throughout the building's life cycle is 1,242 GJ. The materials production stage consumes the highest amount of primary energy (680 GJ) followed by the use stage (484 GJ), while the construction and end-of-life require respectively 1.7 % and the 4.6 % of total primary energy.

Peer-review under responsibility of the scientific committee of the AiCARR 50th International Congress; Beyond NZEB Buildings.

Keywords: Energy life-cycle approach, Embodied energy, Net Zero Energy Buildings, Modular Buildings ;

---

* Corresponding author. Tel.: +39-031-23861977 ; fax: +39-091-484425 .
E-mail address:giovanni.tumminia@unipa.it

Peer-review under responsibility of the scientific committee of the AiCARR 50th International Congress; Beyond NZEB Buildings
10.1016/j.egypro.2017.11.160

Nomenclature

E	Electric energy fed into the grid, kWhe
EER	Energy Efficiency Ratio
E_p	Primary energy, MJ
$E_{pMaterial\ Production\ stage}$	Primary energy consumption during material production stage, MJ
$E_{pConstruction\ Stage}$	Primary energy consumption during construction stage, MJ
$E_{pUse\ stage}$	Primary energy consumption during use stage, MJ
$E_{pEnd\text{-}of\text{-}life\ stage}$	Primary energy consumption during end-of-life stage, MJ
FRP	Fiber Reinforced Material
FU	Functional Unit
GER	Global Energy requirement, MJ
$GER_{no\text{-}renewable}$	Global not renewable Energy requirement, MJ
$GER_{renewable}$	Global renewable Energy requirement, MJ
I	Imported energy from the grid, kWhe
LCEA	Life Cycle Energy Assessment
NZEB	Net Zero Energy Building
PV	Photovoltaic System
SHGC	Solar Heat Gain Coefficient
T_o	Outsite air temperature, °C
VT	Visible transmittance

1. Introduction

Energy efficiency is a key element of European policies aiming to achieve a sustainable and competitive low-carbon economy by 2020.

One of the ways to improve energy efficiency is to act on the huge potential for efficiency gains in the building sector which is the largest single energy consumer in Europe, absorbing 40% of final energy. Moreover, about 75% of buildings are energy inefficient and, depending on the Member State, only 0.4- 1.2% of the stock is renovated each year.

In this context, specific measures with the aim of creating the conditions for a significant decarbonisation of the building sector were introduced by European Union. In particular the key policy instruments towards this goal are the Energy Efficiency Directives [1], which includes provisions to increase energy efficiency at European level, and the European Directive on the Energy Performance of Buildings [2] that introduces the concept of Net Zero Energy Building (NZEB).

Since the primary energy consumption in use stage dominates the entire life cycle of conventional buildings (usually more than 80-85% of energy consumption) [3, 4], the major efforts of these Directives focus on this stage. However, due to the development of high performance buildings the other life cycle stages, such as the construction and the end-of-life, may become the most impacting ones [5].

Therefore focusing exclusively on achieving the NZEB target during the use stage can cause the shifting of the energy and environmental burdens to other life cycle stages. This means that a reliable assessment of the performances of buildings can not be separated from approaching the whole life cycle of the building [6].

In this context, the paper discusses the energy performances of a prefabricated module in Messina (Italy). Its expected main use is temporary housing for workers or for emergency housings.

The use stage performance was studied through dynamic simulation. Thermo-physical modeling was performed in Energy Plus environment [7]. To enhance the solidity of the model a validation was performed by comparing simulated and monitored data.

A Life Cycle Energy Assessment (LCEA) approach was used to assess the life cycle energy performances of the case study. The LCEA was based on the standards of the ISO 14040 series [8, 9] and on the UNI EN 15978 regulation

[10]. The system boundaries were selected according to a "from cradle to cradle" approach, including all life cycle stages of the building, from product stage to end-of-life stage.

2. Case study

The case study is a prefabricated module (Fig. 1), built in Messina (Italy) at the National Research Council. Pultruded fiber reinforced material (FRP) is the main component of the structure.

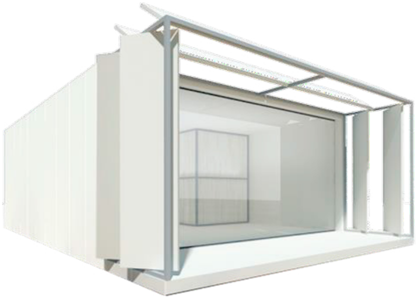

Fig. 1. 3D rendering of the prefabricated module.

Table I reports the main site geographical and climatic data and some building features. The building has an area of 45 m^2, divided into 2 rooms. The building is occupied by three people from 9:00 a.m. until 6:00 p.m., with a break for lunch from 2:00 p.m. to 3:00 p.m. Electric internal loads are caused by lighting, 3 personal computers, a printer and a monitor.

For the south-est façade, a glazed surface covers the whole surface (15 m^2) and it is openable by 20% of the total glazed area. The north-west facade reaches around 65% of window to wall ratio. The windows are made of double low-emissivity insulated glazing with 0.005 m external glass, 0.016 m gap filled with argon and 0.004 m internal glass; the average global window U-value is 1.4 W/(m^2 K), solar heat gain coefficient (SHGC) is equal to 0.3 while the visible transmittance (VT) is 0.4.

Table I – Geographical data and building features.

Geographical data	
Minimum annual temperature [°C]	7.0
Maximum annual temperature [°C]	32.2
Mean annual temperature [°C]	18.9
Mean annual humidity [%]	71.7
Mean annual horizontal solar radiation [Wh/m^2]	367.6
Latitude	38°09′ N
Longitude	15°31′ E
Building features	
Heated floor area (m^2)	45
Walls U-value [W/(m^2 K)]	0.3
Floor U-value [W/(m^2 K)]	0.3
Roof U-value [W/(m^2 K)]	0.3
Window U-value [W/(m^2 K)]	1.4
Window SHGC	0.3

The module is equipped with a grid-connected photovoltaic system (PV) for the production of electricity. The photovoltaic system has a peak power of 3.5 kW_p, with 12 modules of 290 W_p each.

3. Methods

The main aim of the paper is to assess the contribution to primary energy use of each stage of the life cycle of the prefabricated building when compared to the entire life cycle of the building. In order to achieve this goal a LCEA approach was used.

In this method, all the energy inputs required to produce the components, materials and services needed for the manufacturing process are calculated. In detail, it can be represented mathematically by equation (1):

$$E_p = E_{pMaterial\ \mathrm{Pr}oduction\ stage} + E_{pConstruction\ stage} + E_{pUse\ stage} + E_{pEnd-of-life\ stage} \tag{1}$$

where E_p represents the total primary energy consumed during the whole life cycle of a building and Epj represents the primary energy consumed during the j_{th} building stage.

In this study the cumulative energy demand method [11] was used to quantify the GER (Global Energy Requirement) indicator of each stage of the life cycle. Moreover, the GER indicator was also divided into: Global not renewable Energy Requirement (GERno-renewable) and Global renewable Energy Requirement (GERrenewable). The functional unit (FU) is the whole building with a useful life of 25 years.

The system boundaries include the following stages:

- materials production stage;
- construction stage;
- use stage;
- end-of-life stage.

Moreover, in addition to the previous stages of the life cycle, according to [10], the benefits and loads beyond the system boundaries were included in the analysis. In detail, they include the environmental benefits and loads resulting from reuse, recycling and energy recovery resulting from the net flows of materials and energy exiting the system boundary.

The inventory analysis was carried out to quantify the environmentally significant inputs and outputs of the functional unit, by means of bill of materials and energy balances. The following sub-sections describe each life cycle stage modeled.

3.1. Material production stage

For the materials production stage, the quantity of construction materials was estimated through project analysis and investigations of the construction site. The Life Cycle Inventory of building materials includes also the manufacturing to processes to make them ready for the use in the construction process.

3.2. Construction stage

For the construction stage, the approach included the estimation energy consumption, types of transport and scraps due to the building process. The energy use during this stage is due to the electricity needed for machinery and tools. In particular, for the on-site construction of the entire module 150 MJ of energy use is estimated. The data on the transport of materials by manufactures to the construction site were obtained through project analysis (around 1000 km transport for envelope materials, negligible distances for plants).

3.3. Use stage

The use stage was simulated using Energy Plus with a 10 minutes time-step. Simulations used meteorological data from the Meteonorm database [12] for the city of Messina. The model simulates heating and cooling as provided through a heat pump with an energy efficiency ratio (EER) of 3. Lighting power installed is 6.7 W/m^2, controlled by an illuminance dimming system with a setpoint of 300 lux activated by the presence of people inside the building, others electrical loads were included (17 W/m^2). The Equivalent One-Diode model described in [13] was implemented. The Photovoltaic system uses 10 minutes as time-step.

Natural ventilation is modeled through the separate contributions of wind and stack for airflow through the wind formulation and the empirical stack [14]. According to the ventilation strategy adopted, windows open when outside air temperature (T_o) is in the range of $18 < T_O < 26$ °C, the internal temperature is below 23 °C and the wind speed is lower than 2 m/s.

In order to ensure the accuracy of the outputs of the study, the building model was validated. In detail, model validation for existing buildings is accomplished by linking simulation inputs to actual operating conditions and comparing simulation results with building and/or end-use monitored data. A model can be considered validated when the statistical indices demonstrating validation have been met [15].

The case study was validated only on indoor temperature, because the monitoring period was carried out immediately after the completion of the building when it was still not in use. Monitoring was performed during May - June 2015, registering sub-hourly (10 minutes time step) indoor air temperature at different heights, surfaces temperatures, external temperature, solar radiation, wind direction and speed.

Fig. 2 shows the validation results: the differences between monitored and simulated data are below 0.82°C for all data. In 90% of the data, the absolute error is below 0.31°C while for 50% of the calibration data it is below 0.13°C. In addition, the root mean square error of the simulated indoor temperature (0.25 °C), the coefficient of variation of the root mean square error (0.01) and the mean bias error (-0.0012 °C) were calculated and they were found to be lower than those recommended [15].

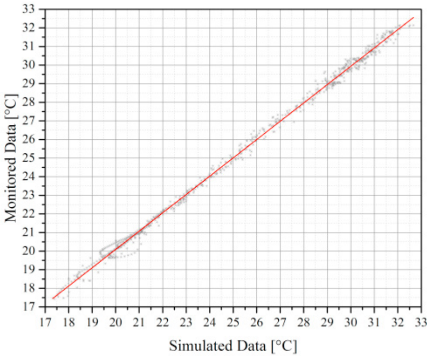

Fig. 2. Validation results.

3.4. End-of-life stage and benefits and load beyond the system boundaries

The end-of-life stage is modelled through secondary data from the Ecoinvent database [16].

Finally, according to [10], the environmental benefits and loads due to the exported energy during the use stage and resulting from the recycling of materials have been allocated in the benefits and loads beyond the system boundaries.

4. Results

Table II reports the simulation results aggregated on a monthly basis for a year of use stage. The yearly electricity demand is about 2,962 kWhe, and it is for the most part due to appliances (70%). Limited impact on the consumptions is due to space heating and cooling (28%) and lighting (2%). The simulated energy demand for cooling are around 18.1 kWhe/m^2, much higher than the heating demand (about 0.6 kWhe/m^2).

Table II – Simulation results for a year of use stage. \

	Lights [%]	Appliances [%]	Heating [%]	Cooling [%]	Total Electricity Use [kWhe]	PV Generation [kWhe]
Jan	6.12	88.58	4.90	0.40	197.84	138.95
Feb	3.75	91.78	2.94	1.53	173.25	209.64
Mar	1.52	81.96	0.52	16.00	220.68	355.55
Apr	0.18	78.52	0.23	21.07	206.72	401.13
May	0.08	74.89	0.02	25.01	241.52	508.57
Jun	0.00	62.58	0.00	37.42	277.36	542.42
Jul	0.00	44.80	0.00	55.20	378.62	594.73
Aug	0.04	45.54	0.00	54.42	397.15	507.07
Sep	0.99	60.17	0.00	38.84	279.13	360.36
Oct	3.99	85.01	0.00	11.00	206.15	263.61
Nov	6.86	87.74	0.23	5.17	197.83	150.53
Dec	6.80	88.35	4.07	0.78	185.59	125.61
Tot	2.02	69.66	0.82	27.50	2961.84	18

Fig. 3 shows the import export balance (IE balance) calculated as in Equation (2):

$$IE\ Balance = E - I \tag{2}$$

where I is the imported energy from the grid (kWhe) and E is the electric energy fed into the grid (kWhe).

Since the overall PV generation (4,158 kWhe) in a year surpasses the electricity consumptions by 1,196 kWhe, the building achieves the NZEB target [17 - 19]. However, for January (- 58.9 kWhe), November (- 47.3 kWhe) and December (- 60 kWhe) the balance is negative even if energy consumptions are lower than those that occur in the summer months. On other hand, the months with the highest IE balance are May (267.1 kWhe), June (265.1 kWhe) and July (216.1 kWhe). This is due to the fact that these are also the months with the largest PV production, respectively 508.6 kWhe, 542.4 kWhe and 594.7 kWhe.

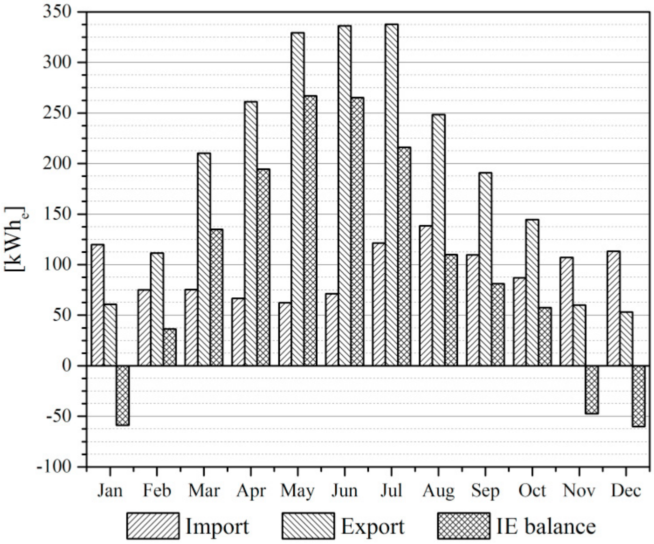

Fig. 3. Simulation results for a year of use stage..

The impact assessment results for the entire life cycle are reported in Fig. 4. These results exclude the environmental benefits and loads due to the exported energy and resulting from the recycling of materials since, according to the regulation UNI EN 15978, they are allocated outside the system boundaries.

The total primary energy use during the building's life cycle is 1,242 GJ (1.1 GJ/(m^2 year)) of which 0.22 GJ/(m^2 year) of renewable energy and 0.88 GJ/(m^2 year) of non-renewable energy. The materials production stage consumes the highest amount of primary energy (54.8%) followed by the use stage (39%), while the construction and end-of-life require 1.7% and the 4.6% of total primary energy, respectively.

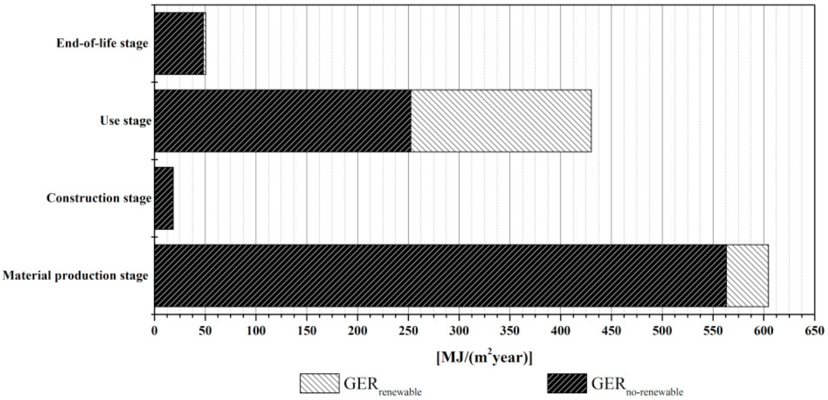

Fig. 4. Simulation results for a year of use stage.

The benefits and loads beyond the system boundaries include the environmental benefits and the loads due to the recycling of materials and the surplus energy exported into the electricity grid. These benefits, although not directly included in the system boundaries, would allow avoiding the production of about 377 MJ/(m^2 year) of total primary energy.

5. Discussion of the results

The material production stage is the most energy intensive stage, while the use stage is the second most impactful one. The building achieves the NZEB objective, since the overall PV generation in a year surpasses the electricity consumptions, but since the on-site generation and consumption are not contemporary, dependency relevant grid dependency is traceable in the case-study. The use of other types of systems fed by renewable energy sources and/or the use of electric energy storage systems might allow a higher load match.

The construction process and the end-of-life stages give a marginal contribution to the total impacts. Since the main construction works are performed outside the construction site, the construction of the building is performed with few easy operations that require a limited amount of inputs. Furthermore, the selective demolition of the building allows to obtain uniform and separated waste and this increase the possibility of recycling the wastes.

6. Conclusions

The study has presented the results of the energy performance assessment in a life cycle perspective of a temporary housing unit built in Messina (Italy). During the use stage, the building is able to achieve the Net Zero Energy Building target by a large extent, with a generation higher by 40% than the consumption.

However, the study demonstrates that reaching the Net Zero target during the use stage could imply the displacement of the environmental impacts to the other stages: this means that the assessment of the performances of buildings can not be separated from approaching the whole life cycle of the building. Thus, the integration of the Life Cycle Assessment methodology in the design choices is of paramount importance to support the development of sustainable buildings.

Acknowledgements

The research was developed in the context of the project: “CNR per il Mezzogiorno – Tecnologie avanzate per l’efficienza energetica e la mobilità ad impatto zero”.

References

[1] European Parliament. Directive 2012/27/EU of The European Parliament and of the Council of 25 October 2009 on energy efficiency, amending Directives 2009/125/EC and 2010/30/EU and repealing Directives 2004/8/EC and 2006/32/EC.). Official Journal of the European Union; 2012.

[2] European Parliament. Directive 2010/31/EU of The European Parliament and of the Council of 19 May 2010 on the energy performance of buildings (recast). Official Journal of the European Union; 2010.

[3] Cabeza LF, Rincón L, Vilariño V, Pèreza G, Castella A. Life cycle assessment (LCA) and life cycle energy analysis (LCEA) of buildings and the building sector: A review. Renewable and Sustainable Energy Reviews 2014; 29: 394-416.

[4] Cellura M, Fontana M, Longo S, Milone D, Mistretta M.. Energy and environmental assessment of retrofit actions on a residential building. In: Salomone R, Saija G, Editors. Pathways to Environmental Sustainability, Methodologies and Experiences, New York: Springer; 2014. p.127-135.

[5] Blengini GA, Di Carlo T. The changing role of life cycle stages, subsystems and materials in the LCA of low energy buildings. Energy and Buildings 2010; 42:869-880.

[6] Cellura M, Guarino F, Longo S, Mistretta M. Energy life-cycle approach in Net zero energy buildings balance: Operation and embodied energy of an Italian case study. Energy and Buildings 2014; 72: 371-81.

[7] Lawrence Berkeley National Laboratory. EnergyPlus,Version 8.4. Berkely, CA; 2015.

[8] ISO 14040. Environmental Management e Life Cycle Assessment e Principles and Framework. Geneva: International Organization for Standardization; 2006.

[9] ISO 14044. Environmental Management e Life Cycle Assessment e Requirements and Guidelines. Geneva: International Organization for Standardization; 2006.

[10] UNI EN 15978. Sustainability of construction works. Assessment of environmental performance of buildings; 2011.

[11] Frischknecht R, Jungbluth N, Althaus HJ, Bauer C, Doka G, Dones R, Hischier R, Hellweg S, Humbert S, Köllner T, Loerincik Y, Margni M, Nemecek T. Implementation of Life Cycle Impact Assessment Methods, Final report Ecoinvent. Swiss Centre for Life Cycle Inventories, Dübendorf, CH; 2007.

[12] Meteonorm website. http://www.meteonorm.com .2015. [accessed 22.01.2016].

[13] Lawrence Berkeley National Laboratory. EnergyPlus, documentation, Engineering reference. Berkely, CA; 2013.

[14] ASHRAE. ASHRAE Handbook: Fundamentals, Atlanta, GA; 2013.

[15] ASHRAE. Measurement of Energy, Demand and Water Savings. ASHRAE Guideline 14-2014; 2014.

[16] Frischknecht R, Jungbluth N, Althaus HJ, Doka G, Dones R, Heck T, Hellweg S, Hischier R, Nemecek T, Rebitzer G, Spielmann M. Overview and Methodology. Ecoinvent Report No. 1, ver.2.0, Swiss Centre for Life Cycle Inventories. Dübendorf, CH, Description of the Ecoinvent database included in the software SimaPro ver. 7.1; 2007.

[17] Cellura M, Guarino F, Longo S, Mistretta M. Different energy balances for the redesign of nearly net zero energy buildings: An Italian case study. Renewable and Sustainable Energy Reviews 2015; 45:100-112.

[18]Marszal AJ, Heiselberg P, Bourrelle JS, Musall E, Voss K, Sartori I, Napolitano A. Zero Energy Building - A review of definitions and calculation methodologies. Energy and Buildings 2011; 43:971-79.

[19] Guarino F, Cassarà P, Longo S, Cellura M, Ferro E. Load match optimisation of a residential building case study: A cross-entropy based electricity storage sizing algorithm. Applied Energy 2015; 154:380-391.