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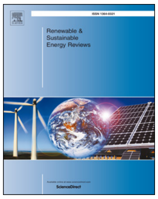

Life cycle energy performances and environmental impacts of a prefabricated building module

Giovanni Tumminia[a], Francesco Guarino[a,*], Sonia Longo[a], Marco Ferraro[b], Maurizio Cellura[a], Vincenzo Antonucci[b]

[a] DEIM Department – University of Palermo, Viale delle Scienze, Building 9, 90128 Palermo, Italy
[b] Institute for Advanced Energy Techonologies "Nicola Giordano" - National Research Council of Italy, Via Salita S. Lucia sopra Contesse 5, 98126 Messina, Italy

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ABSTRACT

The paper explores the energy performances and environmental impacts of a prefabricated building module located in Messina (Sicily, Italy) through an approach that combines both the non-steady state building simulation and the Life Cycle Assessment methodology. The building uses renewable energy technologies and is usable in emergency situations or as simply temporary housing.

Results show that the building module causes the emission of 1.5 t of CO_{2eq}/m^2 and consumes 29.2 GJ/m^2 of primary energy during its life cycle. The building achieves the Net Zero Energy Building target even if it has relevant environmental impacts in the materials production stage (72% on average of the total impacts while the use stage reaches the 23% on average). The construction and the end-of-life stages give a marginal contribution to the total impacts, since they account for the 1% and the 3%, respectively.

1. Introduction

The impact of prefabrication in the whole building market is currently undergoing significant growth. For example, in USA modular/prefabricated housing is expected to reach 140,000 units in 2017, representing 14% annual growth from 2012 [1]. Although prefabricated buildings cannot in any situation replace conventional buildings, they have some characteristics, such as reduced construction time [2], higher safety during construction if compared to traditional buildings (when modular construction is used, reportable accidents are reduced by 80% [3]) and modularity, that make them competitive in specific markets and applications. Prefabricated constructions can also offer environmental benefits, such as limited construction wastes compared to traditional buildings [2]; lower energy consumption during the construction stages [4], lower impacts during the end of life since they can be disassembled and relocated in other sites instead of disposed [5].

However, in a context where the transition towards a low-carbon energy system is quickly becoming an important target of scientific efforts and research, even prefabricated buildings, as well as any other type of building, will have a key role in achieving the decarbonisation of the building sector.

The recast of the EU Directive on Energy Performance of Building [6] specified that by the end of 2020, all new buildings shall be nearly Zero Energy Building (nZEB) defined as very high-energy performance buildings, the energy needs of which are covered at a significant extent by energy from renewable sources, such as solar (photovoltaic and thermal systems), wind, geothermal and biomass [7–9].

Subsequently, over the years, the concept of nZEB has evolved towards that of Net Zero Energy Building (NZEB), a building where, as a result of the very high level of energy efficiency of the building, the overall annual primary energy consumption is equal to or less than the energy production from renewable energy sources on site [10,11].

However, both with the definition of the nZEBs and NZEBs, major efforts to achieve decarbonisation of the building sector are inspired to minimize the energy impacts in the use stage, since the primary energy consumption in this stage is the most relevant in the entire life cycle of conventional buildings (usually more than 80–85% of energy consumption) [12–16]. Nevertheless, focusing only on the use stage does not guarantee the improvement of the life cycle overall performances of buildings. It is instead possible to shift energy use-environmental impacts to the others life cycle stages, such as the construction and the end-of-life [17–19].

This means that the assessment of the performances of buildings assessment should be extended to all stages of the life cycle and should be supported by a Life Cycle Assessment (LCA) methodology approach, that allows the identification of the hot-spots in the buildings' life cycle. Therefore, this methodology can assist with decision-making processes on how to reduce buildings' life cycle environmental impacts [20,21].

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* Corresponding author.
E-mail address: francesco.guarino@unipa.it (F. Guarino).

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Nomenclature

ADP_e	Abiotic resource depletion potential for elements
$A_{opening}$	Window opening area
AP	Acidification Potential
CD	Discharge coefficient for opening
CO	Effectiveness opening coefficient
COP	Coefficient of performance
CV(RMSE)	Coefficient of variation of the root mean square error
EER	Energy efficiency ratio
EP	Eutrophication Potential
F_I	Infiltration schedule
FRP	Pultruded Fiber Reinforced
F_S	Schedule value for the window opening
FU	Functional Unit
g	Generated energy
GER	Global Energy Requirement
GHG	Greenhouse Gas
GWP	Global Warming Potential
i	Time
I_d	Average air infiltration hourly value
l	Total electricity use
LCA	Life Cycle Assessment
MBE	Mean bias error
nZEB	Nearly Zero Energy Building
NZEB	Net Zero Energy Building
ODP	Ozone Depletion Potential
POCP	Photochemical Ozone Creation Potential
Q_s	Airflow rate due to stack effect
Q_w	Wind induced airflow rate
RMSE	Root mean square error
$\overline{T}_m$	Mean of the monitored temperatures
$T_{m,i}$	Monitored temperature
T_O	Outside air temperature
$T_{s,i}$	Simulated temperature
T_Z	Indoor air temperature
W_s	Wind speed
ΔH_{NPL}	Height from midpoint of lower opening to neutral pressure level

The energy performance and environmental effects of traditional buildings have been previously studied [12–17], while a limited number of works about prefabricated construction is available [22–32]. In the following paragraphs, some literature studies on prefabricated buildings are discussed: most of them do not take in consideration the entire life cycle of the building, and if they do, the approach is usually simplified or a detailed building performance simulation analysis is missing.

Cao et al. [23] compared the environmental impacts of a residential prefabricated building with a traditional building through the application of LCA. Both buildings are located in the Fangshan District of Beijing, China. The prefabricated building is made of the assembly of precast concrete wall systems. The prefabricated elements account for approximately 38% of the total volume of the prefabricated building. The traditional building has a reinforced-concrete wall structure and it relies on the traditional cast-in-situ construction method. The system boundaries for both buildings included materials extraction, off site component manufacturing, transportation, construction and on site - assembling. The results showed that the prefabricated building construction is less energy intensive: it has a total final energy consumption lower by 20.5% if compared to the traditional building. Moreover, the use of prefabrication showed lower environmental impacts, e.g. 35.8% reduction in resource depletion, 6.6% in health damage and 3.5% in ecosystem damage.

Atmaca [24] addressed the life cycle primary energy consumption and the CO_2 emissions of the construction, use and end-of-life stages of two temporary houses (a prefabricated house and a container). The buildings life cycles were assumed to be 15 and 25 years for the container and the prefabricated building, respectively. The one-storey prefabricated building has a gross area of 70 m^2, two rooms, one kitchen and a sitting room. The container is a small building with a gross area of 21 m^2, with two rooms, a toilet and a kitchen inside the room. Life cycle primary energy consumption of the prefabricated and container housings are calculated to be 29.1 and 32.6 GJ/m^2, respectively, while the CO_2 emissions were respectively 255 kg CO_{2eq}/(m^2 year) and 491 CO_{2eq}/(m^2 year). The use stage is the most relevant stage over the life cycle of the housings, accounting for 85.9% and for 90.3% of total primary energy use of the prefabricated and container respectively and for 94.6% and 95.7% of total CO_2 emissions. Finally, the results show that the prefabricated housings compared to the container allowed saving 15% of primary energy use and avoiding 92% of the CO_2 emissions.

Faludi et al. [25] performed a LCA, from the material acquisition to the end-of-life, of a prefabricated modular commercial building (465 m^2) in San Francisco. The building has a structural steel frame with light-gauge steel wall panels and aluminum curtain walls. Three different energy consumption scenarios for the operation stage are analyzed: 1) standard building with average Northern California energy use; 2) 30% of the energy supplied by rooftop photovoltaics and the rest by the grid; 3) a NZEB (photovoltaic system supplies 100% of energy requirements). The lifetime of the building is estimated to be 80 years. Energy consumption in the use stage is estimated through a non-steady state simulation. The result show that the standard building is the worst scenario (during the entire life cycle about 3000 t of CO_{2eq} emissions and around 180,000 EcoIndicator 99 points) while the NZEB building is the best scenario (around 500 t of CO_{2eq} emissions and approximately 40,000 EcoIndicator 99 points). Results also show that energy consumption in the operation stage causes the highest impacts (83% of CO_2 emissions) in the standard building. In the third scenario the most impactful stage is the material production (55% of CO_2 emissions).

In the study of Monahan and Powell [26] a “from cradle to construction site” LCA of a low energy modular building is performed. The building constructed in 2008 in Norfolk (United Kingdom) is based on timber frame wall modules,. In addition to the case study (base scenario), two further scenarios (scenarios 2 and 3) are modelled. Scenario 2 uses a panelized modular timber frame with steel cladding, while the third scenario is a traditional masonry building. For the base scenario, the total embodied energy is 5.7 GJ/m^2 while the embodied carbon is approximately 405 kg CO_{2eq}/m^2. The 82% of the total embodied carbon is due to materials. In scenario 2, the embodied energy and carbon is 7.7 GJ/m^2 and 535 kg CO_{2eq}/m^2, respectively. This means embodied energy and carbon are higher by respectively 35% and 32%is if compared to the base scenario. Scenario 3 is the worst scenario (8.2 GJ/m^2 and 612 kg CO_{2eq}/m^2). If compared to the base scenario, this case shows both embodied energy and embodied carbon higher by respectively 35% and 51%.

Mao et al. performed a LCA [27] of two types of buildings in Shenzhen, China: a prefabricated building and a traditional one. System boundaries include building materials production and transports, transports of soil, transports of prefabricated components and buildings construction. The aim of the study is the determination of the extent of the reduction of Greenhouse Gas (GHG) emissions that can be achieved by prefabrication in comparison to conventional construction. A reduction of 1.1 t of CO_{2eq} per 100 m^2 is estimated, approximately 3.2% lower than the conventional building. The main contributor to GHG emissions reduction was the embodied emissions of building materials,