Life Cycle Assessment and Zero Energy Residential Buildings

MICHELE PALEARI[1], MONICA LAVAGNA[1], ANDREA CAMPIOLI[1]

[1]Politecnico di Milano, Architecture, Built Environment and Construction Engineering Dep., Milano, Italy

ABSTRACT: The European Directive n. 2010/31/EU aims to improve the environmental conditions working on the reduction of the energy consumptions in the use phase. For this reason, it requires that all new buildings completed after 2020 will have in use consumptions close to zero (nearly-Zero Energy Buildings). Therefore, this research has the goal to verify the environmental efficiency of residential nZEB, considering the overall impacts generated in all lifecycle stages. With this aim, an LCA evaluation was carried out on a residential complex nZEB built with traditional technologies and located near Milano, in Italy. The final outcomes highlight that the pre-use phase (materials production, transport and construction activities) amount to 56% of the total impacts and the use phase (use and maintenance) counts for 41%. Moreover, the impacts connected with the building operation are limited to 31% of the total: this suggests that analyzing the operational stage means to worry only about 1/3 of the real impacts.
Keywords: Life Cycle Assessment, Zero Energy Building, residential buildings.

INTRODUCTION

Since about 40% of European energy consumptions are linked to the construction sector, the achievement of the environmental targets set by the Kyoto Protocol requires a crucial action to reduce the impacts caused by buildings. In this context, the European Directive n. 2010/31/EU (EPBD recast) [1] constitutes the high point of a long regulatory process which aims to improve the European environmental conditions working on the reduction of the energy consumptions in the operational phase of buildings. For this reason, it requires that all buildings of new construction completed after 31st December 2020 will have an operational energy consumption close to zero; in other words they will be nearly-Zero Energy Buildings. Facing with this scenario, we conducted a research with the aim to verify the environmental efficiency of nearly-Zero Energy Buildings, considering the overall impacts generated during all stages of their lifecycle. The focus of the Directive is to minimize the energy consumptions in the use phase, without any verification of the reduction of the overall environmental impacts and the overall sustainability (economic and social).

THE REGULATORY FRAMEWORK

The Directive n. 2010/31/EU of the European Parliament and of the Council was enacted on 19th May 2010 and it is entitled “On the energy performance of buildings”. It is the recast of the previous energetic Directive n. 2002/91/EC and, proceeding on the same line, it aims to achieve the environmental objectives expressed by the Kyoto Protocol, through the progressive reduction of the operational energy requirements of buildings. In this context, the concept of nearly-Zero Energy Building is understood as the achievement of so efficient performances that the energy requirement can be satisfied through the production from renewable resources, preferably on the building itself or within its site. However, the concept of “nearly zero” is not numerically defined by the rule but the responsibility about this is delegated to the Member States.

Concerning the methodology applied, we refer to the substantial regulatory work that the Technical Committee 350 of CEN is conducting for several years with the aim of defining a framework for the sustainability assessment of buildings and construction works. The rules already published constitute a reference framework useful to address the issue of the sustainability assessment with a comprehensive approach, in other words, taking into account both the environmental aspects and the economic and social ones. In addition, the strictly energetic approach of the Directive n. 2010/31/EU is replaced with a broader perspective based on the lifecycle analysis of buildings and on the assessment of numerous indicators of impact. Therefore, the standards EN 15643 [2, 3] and EN 15978 [4] prescribe that the assessment of the environmental profile of the construction works should be carried out by applying the Life Cycle Assessment methodology, standardized by ISO 14040 and ISO 14044.

THE CASE STUDY

The evaluated case study consists of a residential complex located in a small town in the East hinterland of Milano, in the northern region of Italy. It is composed by 4 buildings with linear typology arranged around a central courtyard, with a total of 61 apartments of various sizes. We choose this complex as an example of a type of building which certainly will be built in the next few years to be in compliance with the Directive n. 2010/31/EU. This is because traditional typologies, materials and construction techniques were joined with targets of high energy efficiency and devices for the on-site energy production, in order to build a complex classifiable as a near ZEB. More in detail, the load bearing structures are made by reinforced concrete, with the lightening brick blocks in the slabs of the residential parts. The perimeter walls are made by thermal bricks blocks with an external insulation in rock wool panels; even the internal partitions are in bricks with traditional plasters composed by cement, clay and sand. The roofs structures are made of glue laminated wood; the pitches are insulated through rock wool panels and a multilayer reflective insulation made with aluminium sheets and expanded polyethylene layers; the finishing pitches surfaces are in concrete tiles. All the windows and the external doors are made by PVC profiles, with high insulation performance double glazing, while the skylights on the roofs and the internal doors are made by wood. The winter heating, the summer cooling and the domestic hot water production are assured by a single thermal plant, run by a central heat pump that takes advantages from the horizontal borehole heat exchanger built under the underground basement. All the common services are fed with electric power that is partially produced through the polycrystalline silicon photovoltaic panels installed on the roofs and on the other structures built in the northern garden. The photovoltaic installations are able to provide the total energy requirement of the heating plant and about 50% of the energy needs for the domestic hot water production.

The total net floor area is about 4,000 m^2 and the surfaces of the residential ancillary spaces, like unheated attics, stairs and technical rooms, amounted to about 4,000 m^2. The buildings are placed on a large underground basement which includes 90 garages, some technical rooms and ancillary spaces, for a total area of approximately 7,000 m^2.

It should be noted that this complex is the result of a private real estate initiative conducted by a building contractor and it was conceived, designed and partly built before the adoption of the Directive n. 2010/31/EU.

THE METHODOLOGY

On the residential complex just described we conducted an environmental assessment LCA, according to ISO 14040, ISO 14044, EN 15643 and EN 15978. We managed all the quantitative data through many Excel spreadsheets while the environmental assessment has been carried out with the assistance of the software SimaPro 7.3.2. The environmental data were found in the Ecoinvent database, while we described the results of the evaluation with the indicators of the EPD2008 method, Global Warming Potential, Ozone Layer Depletion Potential, Photochemical Oxidation Potential, Acidification Potential, Eutrophication Potential, Non-Renewable Energy Resources. We chose this set of indicators because it is prescribed in the EN 15643-2. We set the functional unit as the whole residential complex and we took into account all the stages of its lifecycle, compared to a life scenario of 100 years.

THE SYSTEM BOUNDARIES

At the beginning of the evaluation process we decided that our aim is to evaluate the complex in its entirety, including all the materials, the work and the processes involved. Later, during the collection of all the data to be included in the inventory, insurmountable difficulties occurred and therefore they forced us to exclude certain components from the evaluation process. As the physical boundary of the system coincides with the boundary of the site of the project, in accordance with the EN 15978, we took into account all the activities inside the building and the area of its relevance in the construction, use and maintenance. We included also the stages of pre-production, production, transport to the building site and end of life.

With regards to the transformation processes, we identified the materials consumed in the construction, such as concrete, bricks, wood, steel for reinforcement bars and carpentry, plasters, insulation materials, and to all of them we assigned the impact values found in the database. In the assessment we also included the semi-finished products and the complex components to which it was possible to assign the impact value of the main materials. On the contrary, we excluded all those components for which we were not able to gather all the necessary information about the composition, the production process and the environmental impacts. Some examples are the components of complex systems such as hydraulic pumps, motors for the movement of windows, light fixtures, switches, thermostats and elements of the electrical system. The assessment also excluded the entrance doors of the apartments, the interior doors, and plasterboard ceilings.

After the pre-production phase, we analyzed the transport phase through the specific and as detailed as possible reconstruction of the itineraries of the raw materials and the semi-finished products, following the subsequent production steps. In particular, we have tried not to interrupt the quantification of the routes to only storage centres, of which it is relatively easy to detect the geographic position, but, as far as possible, also the intermediate steps have been reconstructed. We assumed the useful information from the producers and the sellers.

After that, we assessed the construction phase, identifying the quantity of material input and output, the consumptions of electric power and drinking water, the fuel consumption for the operation of the main operating machines. The main consumable materials of the construction site, as timber and protective sheets of polyethylene, were included. On the contrary, minute materials which are difficult to quantify, such as screws, fasteners and accessories in general, were excluded. It was possible to access the registry of wastes leaving the site, thus defining the quantities of debris from construction/demolition, wood, EPS, polyethylene, paper and cardboard used for the packaging of materials and components. To the voice of building site waste we also associated the impacts resulting from the transportation of the materials to the centre of separation and storage and then to the final disposal or to the processing industry.

With regards to the use phase, we took into consideration the consumption of electricity which can not be satisfied from the on-site production related to the presence of the photovoltaic plant. Within the consumption of the building, we highlighted the need for the production of the domestic hot water and for the operation of the heat pump during the cooling phase, while it was not possible to envisage the consumption of electricity for lighting the common areas nor enough data were collected after the entry into operation.

Downstream from the use phase, we computed the impacts resulting from the end of life scenarios assumed for the materials and the components consumed during the construction.

DATA COLLECTION

The retrieval of the data needed to fill the inventory on which base the environmental assessment has been carried out through the examination of 4 different types of documents: the invoices paid by the construction company that financed the entire real estate activity, the SAL (Stato Avanzamento Lavori) prepared by the subcontractors, some drawings and documents of the final and the construction project, a great number of product data sheets. In addition, many detailed information were acquired through the dialogue with the owner of the construction company, the site manager, some technical or trade employees of the subcontractors, the manufacturers and the suppliers of the building materials. It is important to emphasize that the construction process of this residential complex implied the activation of numerous contracts attributable to two different types. The first one is related to contracts for the supply of materials and components and was stipulated between the client and some producers or traders; the second type is linked to the supply of services and complete works, so to contracts stipulated between the customer and about 15 subcontractors. The key difference for the construction of the inventory is that, on the one hand, the supply contracts give rise to very detailed invoices which describes materials and purchased products, their quantity (in kg, m^3, m^2 or number of units), their unit prices and their total prices. In some cases the price for transport or for ancillary activities connected to special processing inside the factory (such as cutting and polishing of the stone slabs for the floors) or in the building site (for example, the pumping of concrete for the construction of the load bearing structures) are recorded separately. In some cases it is also mentioned the item of the supply of auxiliary materials such as adhesives or fixing devices. On the other hand, the sub-contracts give rise to very synthetic invoices, generally labelled “Opere come da contratto” and show only the total cost. In these cases it was necessary to resort to specific SAL which show the complete description of the works carried out and the list of materials and components used; this is the case of the plant supplies. The SAL are generally processed once a month by the company that carries out the work and are approved by the building site manager to confirm the accuracy of the data quantity. These documents show the description of the materials used, their quantities, their unit and total costs, as well as the description of the processes.

The data collection was carried out through the examination of more than one thousand invoices and over fifty SAL and reports from the construction site. The invoices were classified into two main categories (purchase of materials and provision of services or complete works), then grouped according to the company name. During this work we gathered all the possible information about the products, their amount and their costs; after that we proceeded to the next steps, to aggregate the information in order to understand which were the materials to be included in the inventory and what were the amount to be associated with each material. During this process, the consultation of the final architectural design, the executive project of the precast concrete beams and of the glue laminated wood structures of the roofs and of numerous product technical sheets was crucial to better understand the constituent materials of each product, the quantities to be considered, the places of production and any intermediate process operated by companies other than the one who marketed the products. At the same time, we also collected all the available information to determine the itineraries of goods for the assessment of transport impacts. This process allowed us to identify nearly 100 entries that make up the inventory of the materials consumed for the construction. It is to be noted that the amounts of certain materials were expressed both according to the typical marketing unit of measurement (m^3, m^2 or pieces) and in terms of weight in order to calculate the impacts of transports.

THE MATERIALS PRODUCTION

To examine the results of the environmental assessment it appears immediately clear that the materials used to construct the load bearing structures cause impacts between 40% and 60%, followed by the materials for finishes and those for plants. The unexpected result is the fact that the impacts linked to the latter two categories are higher than those generated by the materials of the “building components” in the strict sense, like masonries, insulations and windows. In some cases, the category of finishes has a relevance similar to or even greater than the sum of masonry, plaster, insulation, waterproofing and window frames.

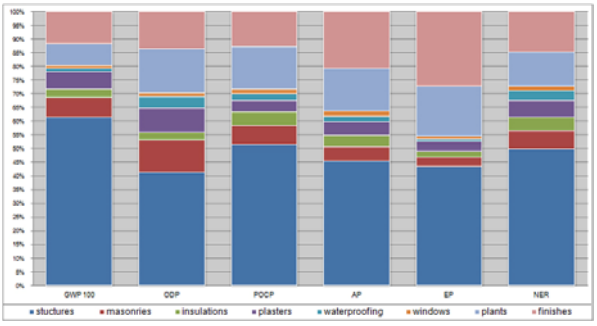

Figure 1: Impacts in the production stage.

The results of the calculation of the energy consumptions from fossil fuels show that 50% of the impacts is due to materials for load bearing structures, followed by finishes which account for 15% and by plants components, with 12%. The sum of the energy consumptions of walls (6%), plasters (6%) and insulations (5%) slightly exceeds the energy consumption due to the production of materials for finishing. The impacts of waterproofing materials are 3%, while the windows are the last category with less then 2% of the impacts. If evaluating the amount of energy consumed, the materials for the structures have absorbed about 45,800 GJ, the finishes 13,700 GJ, the plants 11,500 GJ and the building envelope 17,800 GJ. The production of materials used in the construction of the building complex consumed a total amount of 92,200 GJ of energy from fossil fuels; if this value is normalized in relation to the building surfaces, we point out that every square meter of the net floor area absorbed almost 23 GJ. Furthermore, if we also consider the surfaces of the ancillary spaces such as attics, terraces, balconies, cellars and the common spaces of buildings (8,000 m^2), the energy consumption is reduced to 11 GJ or 114.1 MJ/m^2y on a scenario of 100 years, which is equivalent to 31.7 kWh/m^2y. This value decreases till 83.3 MJ/m^2y or 23.1 kWh/m^2y considering also the basement area for garages and for manoeuvre.

With regards to the indicator of the Global Warming Potential, the materials of the load bearing structures certainly have the highest impact and reach 61%. This value is followed by the materials for finishes (12%) and for plants (8%), which have more significance than masonries (7%) and plasters (6%). It should be stressed that this is the category of impact where the structures have the greater weight, in contrast with finishes and plants which mark their minor impacts. The insulating materials have much lower impacts (3%), while the contribution of waterproofing materials and windows is very marginal, as it is just over 1%. In quantitative terms, the structure components are responsible for the emission of about 5,000 t of CO_2 equivalent, the finishes of 960 t and the plant elements of 660 t. The total volume of CO_2 equivalent emitted by the materials consumed for the construction of the building complex is about 8,100 t, equal to 2 t per square meter of residential floor area (4,000 m^2); this value is halved if the total emissions of greenhouse gasses are related to the sum of the net floor area and the ancillary spaces area (8,000 m^2).

The indicator on which the materials for the structures have the least influence is the Ozone Layer Depletion Potential: only 41%. To the contrary, masonries, plasters and waterproofing materials show here their highest impacts, reaching, respectively, 12%, 9% and 4%. The second and the third categories, after the load bearing structures, are again plants (16%) and finishes (14%), while windows represent always the less impact category (1%). The overall impact of building materials amounts to 0.46 kg CFC-11 eq.

The Photochemical Oxidation Potential is the indicator where the insulations have their greatest influence, touching 5%, and where the windows rose to nearly 2%, even if the structures are always the heaviest category, which in this case exceeds the threshold of 50%. The windows components generate their greatest impacts on the indicator of Acidification Potential with 2%. About this indicator it is very evident the importance of the elements for finishes and plants. The first category reaches 21%, which is a greater value than the sum of the impacts caused by the other subsystems, with the exception of structures and plants, while the latter category, with 15%, exceeds the sum of masonries, insulations and plasters.

If we examine the Eutrophication Potential, we realize that all the categories have impacts with lower percentages than what we observed in the case of Acidification Potential, with the exception of finishes and plants, which mark their highest impacts. The sum of the building components in fact amounts to only 11%, against 18% of plants and 27% of finishes and this is the only environmental indicator on which the sum of the latter two categories exceeds the impacts caused by the production of materials for structures. This result is mainly due to the use of copper for plant components and for gutters and pluvial.

THE WHOLE LIFE

If we analyze the final outcomes of the overall assessment, we can point out that the pre-use phase, divided into materials production, transport to the building site and construction activities, as a whole amounted to 56% on average. The impacts caused by the use phase count for 41% but the part directly connected with the building operation is limited to only 31%. This suggests that analyzing the environmental profile of this residential complex considering only the operational consumptions means to worry only about 1/3 of the real impacts. Moreover it is necessary to remember, as repeatedly explained, that the analysis of some components was excluded due to a lack of quantity data, then the relationship between the parties may actually be even more unbalanced.

With regards to the construction phase, we highlight that the impacts caused by the transport of semi-finished products to the construction site and the impacts of the construction process on average are equivalent to 7%. This means that excluding certain phases of the evaluation leads to a change in the results that is not predictable before the analysis and that is certainly not irrelevant. Moreover, among the impacts of the building site we remember that, in this case, the disposal of the lands of excavation caused significant impacts because of the large quantities involved. Finally, taking into account the operational phase, it can be stated that, despite the photovoltaic plant produces electrical energy sufficient to cover the requirements for heating and partially that for the production of domestic hot water, the comparison between the impacts linked to this phase and those caused by the previous one fail to balance even at the end of the useful life of the building. The operational energy consumptions after 100 years amounted to 69,200 GJ, that are equivalent to 24 kWh/m^2y; the emissions of greenhouse gases correspond to 4,500 t CO_2eq., that are 5.6 kg of $CO_2eq./m^2y$.

The values vary according to the considered indicators: the pre-use phase impacts less on Ozone Layer Depletion Potential (45%), it has more significance on the consumption of energy from fossil fuels (54%) and reaches maximum values in terms of Global Warming Potential (61%) and Photochemical Oxidation Potential (65%). On the contrary, the use phase has very high impacts on ODP (41%) and lower in terms of resource consumption (36%) and GWP (30%). The higher environmental impact of the phase of transport is on the POCP, with almost 6%, while the emissions of greenhouse gasses caused by the construction activity climb up to 6%.

The total consumptions of non renewable resources, after 100 years of life, may be listed in 193,950 GJ, equivalent to 240.2 MJ/m^2y or 66.7 kWh/m^2y, normalized on 8,000 m^2; the greenhouse gasses emissions amount to 15,300 t, corresponding to 18.9 kg of $CO_2eq./m^2y$.

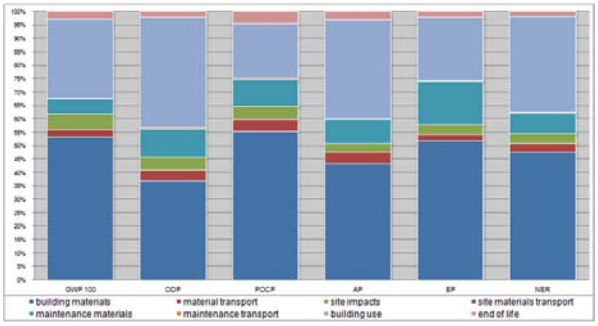

Figure 2: Impacts in the whole lifecycle.

The final results are quite difficult to compare with those described by other authors and available in literature. The reasons are mainly due to the specific differences between the case study analyzed and the other buildings evaluated; moreover some researchers consider only certain phases of the lifecycle, sometimes taking information from literature about the impacts of production, transport or construction. Finally, the fact that this complex is a nearly-Zero Energy Building implies a drastic reduction in the use stage impacts from about 80% or 90% to only 30%-35%, as reported for instance by Cuellar and Gustavsoon [5, 6]. We underline also that in this case study we consider only the energy consumption related to the building requirements, in compliance with the EN 15978, and we exclude the consumptions for the inhabitants' uses. In contrast, some researches counted also the electricity consumptions related to the residents' needs. Finally, the accurate analysis of the itineraries made by building materials allow us to calculate the impacts of transports more precisely. For this reason, the final weight of transports is 7%, that is much higher than what reported by other authors who place the impact for transport between 1% and 3% [6, 7].

CONCLUSIONS

In conclusion, the verification of the environmental effectiveness of near-Zero Energy Buildings proposed by the Directive n. 2010/31/EU gave a negative result and we believe that the implementation of this solution could bring long-term environmental results below than what expected. The main reasons for this negative opinion can be summarized in four main topics which are discussed here below.

In the first place, focusing the attention exclusively on the assessment of the energy consumptions related to the use phase involves the gradual and inexorable displacement of the environmental impacts to the other phases, with a prevalence towards the production of the building materials. The excessive attention paid to the operational energy consumption and the concomitant lack of control on the other stages of the lifecycle involves the reduction to almost zero of the environmental burden of this phase but it does not guarantee in any way that the overall balance will be improved compared to the actual conditions already in place. In particular, depending on the design and the manufacturing choices, it is possible to obtain an improvement in the environmental profile of the building without cancelling the use phase but through the reduction of the impacts during the production stage or increasing the useful life of the components with a consequent decrease of the impacts linked to the maintenance activities. In this case study, the impacts due to the pre-use amount to 55%, compared to only 31% of the operational phase.

Secondly, focusing the attention on the energy consumptions means to take into account only the heated rooms of the building. However, each building has numerous unheated spaces with different functions and they generate environmental impacts mainly during the materials production, the construction and the end of life stage. If the sum of the all the ancillary spaces, that are the non-residential ones, the parking spaces and the not accessible areas, is greater than the net residential floor areas, the environmental profile of the construction may be strongly influenced, particularly in the case in which the majority of these surfaces are placed below the ground level. This specific case study presents a very large basement determined by the choice to include a heat exchanger in the horizontal foundation slab; this fact led to the over-sizing of the foundation and consequently the amplitude of the underground spaces. We note that 54% of the materials delivered to the building site, considered in terms of weight, has been consumed for the construction of the underground structures and its coverage.

A typical issue of Zero Energy Buildings is related to the research of the energy self-sufficiency which leads to a substantial increase in plant equipments of the building; they aim both at the on-site production and at the energy management and at the increasingly sophisticated control of the indoor environmental conditions to optimize the energy consumptions. The plant components associate an overall limited weight, when compared to the building components, but are produced starting from raw materials which cause major environmental impacts (metals and plastics) through industrial cycles complex and articulated. In addition, due to the specific nature of the building process, the evaluation of the plant components is more complex than the assessment of the building elements and, for this reason, it is often overlooked. The increase in the density and in the complexity of plants causes the enlargement of the environmental impacts not only in the early stages of production and construction but also worsens the burden of maintenance. This is because the plant components are characterized by a lifespan shorter than the useful life of the building, which can be plausibly estimated as 100 years, in the Italian context. Moreover, in recent decades the plant components have been subject of technological advancements stronger than those affected the building products; many innovative solutions were experimented but their effectiveness in the long period is quite uncertainty. In the case study just presented the production of plant materials causes on average 14% of the impacts for the production of all building materials, compared to a very limited impact in terms of weight.

Finally, the strong increase in the operational performances makes necessary to continuously monitor the level of efficiency of all components and increases the likely maintenance activities which entail significant economic burden. If the building users are not able to financially support all the necessary maintenance, the energy performance of the building could get worse in a few years, bringing the ZEB to the status of a conventional building and impairing the efforts made in the design and in the construction of the solutions which aim to energy efficiency. In relation to this aspect, we emphasized that the purchase of the plant components installed in this case study resulted in 32% of the initial cost and in the whole lifecycle their maintenance can be estimated as 20% of the total cost. In contrast, the environmental impacts due to maintenance activities are limited to 10% of the impacts on the lifecycle.

To summarize, the answer given by the Directive n. 2010/31/EU to the need to reduce the environmental impacts linked to the construction sector turns out to be partial because it excludes many aspects that greatly influence the environmental profile of buildings and on which is fundamental act to improve the environmental conditions.

REFERENCES

1. Directive 2010/31/EU of the European Parliament and of the Council of 19 May 2010. On the energy performance of buildings.
2. CEN (2010). EN 15643-1:2010. Sustainability of construction works - Sustainability assessment of buildings - Part 1: General Framework.
3. CEN (2011). EN 15643-2:2011. Sustainability of construction works - Sustainability assessment of buildings - Part 2: Framework for the assessment of environmental performance.
4. CEN (2011). EN 15978:2011. Sustainability of construction works - Assessment of environmental performance of buildings - Calculation method.
5. Cuéllar-Franca, R.M. and Azapagic, A. (2012). Environmental impacts of the UK residential sector: Life cycle assessment of houses. *Building and Environment, 54*: p. 86-99.
6. Gustavsson, L. and Joelsson, A. (2010). Life cycle primary energy analysis of residential buildings. *Energy and Building, 42*: p. 2010-2020.
7. Blengini, G.A. and Di Carlo, T., (2010). The changing role of life cycle phases, subsystems and materials in the LCA of low energy buildings. *Energy and Building, 42*: p. 869-880.