BENIMPACT Suite: a tool for ZEB whole life cycle analysis

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Abstract

The building sector is predominantly responsible for energy consumption and environmental impact in the European Union. For this reason the European legal framework related to this sector has had a huge evolution over recent years. The "nearly Zero Energy Building" (nZEB) concept was introduced in 2010 with the Energy Performance Building Directive (recast) 2010/31/EC which stated "…zero consumption as a long-term goal for our buildings…". By 2020 all new buildings will have to be "nearly Zero Energy" (nZEB) and the majority of their energy consumption has to be covered by renewable sources. It is important to underline that the definition nZEB does not concern only the energy efficiency of a house, but also the environmental impact and the life-cycle cost of the adopted solutions. Designing and realizing such buildings is a very ambitious task, which needs to be supported by appropriate tools and software. This paper presents BENIMPACT Suite (Building's ENvironmental IMPACT evaluator & optimizer): a new tool for assessing buildings' performance, developed by EnginSoft (Italy). The suite is organized in different core modules which allow to verify how the building performance is influenced by different design choices, such as envelope shape and materials, plant systems, renewable sources use, etc. One of the test cases used to validate BENIMPACT Suite is CasaZeroEnergy, a ZEB concluded in 2010 and located in Felettano (UD), in north-eastern Italy. This building is an experimental house designed and monitored by the Laboratory of Building Design of the University of Trento (Italy) and built by Polo Le Ville Plus Group (Cassacco-Italy). Energy performance, renewable energy production and Life Cycle Assessment of this building were modelled and evaluated using the BENIMPACT Suite and simulation results were compared to monitored and literature data.

1. Introduction

We want the buildings in which we live to be safe, healthy, functional, comfortable, and also aesthetically integrated into the urban context. They also need to be properly designed to be energy efficient and environmentally friendly to contribute in minimizing environmental loads, according to the international framework on building sustainability.

1.1 European regulation: an overview

Ten years ago, in 2002, the first Energy Performance of Buildings Directive (EPBD) 2002/91/EC was released in order "to promote the improvement of the energy performance of buildings within the Community, taking into account outdoor climatic and local conditions, as well as indoor climate requirements and cost-effectiveness". Minimum energy performance was required for new buildings and existing buildings which were subjected to major renovations.
Since then, sustainable design and green strategies applied to the building sector have become more and more popular among governments, designers and researchers. Solar passive design and energy performance, insulation thickness increment, plant equipment improvement, renewable resources on site systems have become a trend. Adopting a benchmark energy performance level made it possible to drastically reduce energy consumption in buildings.
With the aim to reduce negative impacts from the building sector, and to help a faster diffusion of "smart" design strategies, the European Union has introduced several policies and regulations. Some examples are the following directives: the

2005/32/EC on Energy using Products (EuP), the 2006/32/EC Energy Saved Directive (ESD) on energy end-use efficiency and energy services, and its new version, the 2009/125/CE on Energy related Products (ErP). The Directive 2009/28/EC promotes the use of energy from renewable sources and requires that Member States should fix, by 2015, a minimum level of energy from renewable sources for new buildings and existing buildings subjected to major renovation.

The most important release of this general framework is the revision of the 2002 EPBD, the 2010/31/EC, known as Energy Performance of Buildings Directive (recast), which requires zero consumption as a long-term goal for European buildings. The recast fixes 2020 as the deadline for all new buildings to be "nearly Zero Energy" (for public buildings the deadline is the end of 2018): very high energy performance, and very low or almost zero energy demand, mostly covered by energy from renewable sources produced on-site or nearby. Nevertheless, the current system's boundaries only consider the energy consumed for building management. Energy and environmental impacts from the other phases of its life cycle (material production, construction, maintenance, dismissing) are totally omitted, although it has been demonstrated that this amount of energy and sources gives an average contribution of 30% of the overall impact (Sartori and Hestnes, 2007). This value can rise up to 50% for low energy buildings.

1.2 Barriers in achieving the nZEB target

ZEB could strongly help to reduce energy consumption, environmental loads and operational costs. Even if the development of energy efficient constructions is strongly stimulated by legislative requirements, there is still a wide range of non-technological barriers that must be overcome in order to reach a wide diffusion of the zero energy building standard.

First of all, extra initial costs are far from the construction business's mind. Usually, both contractors and clients are mainly driven by short-term profit-making and focus on the lowest price bidding and not on the added value that can be achieved implementing environmentally friendly measures. Furthermore ZEB are not usual constructions. They need a high level of knowledge and skills that are not always available in design and construction teams. Several professionals are involved in the design process, and this might lead to problems if there are lapses in the communication among the different project team members. All actors must fully understand the issues and concerns of other parties and interact closely throughout all phases of the project. This is why an integrated design approach is needed to achieve multiple benefits such as higher efficiency and cost effective buildings. One of the main problems is the lack of tools needed by project teams to coordinate their work and to consider and evaluate different design alternatives.

In most mechanical industrial fields, ranging from aerospace to bio-mechanics, sophisticated 3D computer simulation tools have been used to predict responses to specific forcing actions in specific environments in order to integrate all the opportunities offered by different materials and technologies. The same kind of tools should be used in the construction sector. Although many are trying to develop a standard Building Information Modelling (BIM), there is currently no software able to take into account all the features that a ZEB shall have. Thus, there is an evident need to develop software for buildings design that can help to predict how the building will perform and enable them to model economic and environmental consequences of different design choices.

2. BENIMPACT Suite

2.1 Short overview on BENIMPACT Suite

BENIMPACT Suite wants to be a way to promote integrated design Computer-Aided Engineering (CAE) and intelligent Digital Prototyping (iDP) in the housing field.

BENIMPACT Suite is composed by different modules (Energy, LCA, Cost) that can work both as a standalone or as an integrated system (Global evaluation and Optimization). It should turn into a complete suite, whose aim is to help designers

check the quality of their solutions and find the "optimal" set of choices between different alternatives of building envelopes and energetic systems. It analyzes the whole life cycle of a building and searches for the "optimal" trade-off between opposed goals: energy consumption, environmental impact and cost Indeed, in order to achieve the highest level of independence from traditional fossil fuel sources and the lowest environmental impact (materials use, energy consumption and pollutant emissions into the atmosphere), every new building must be designed straight from the preliminary phase so as to maximize all the chances given by the natural environment and by current technologies..

If the final aim is to spread awareness of sustainable design in a spontaneous way, the necessity to design "environmentally friendly" constructions must be compatible also with the amount of investment. We believe that the opportunity to find "smart" solutions will lead to an increment of sustainable buildings (new or renewed ones), less natural source depletion and a reduction in greenhouse gas emissions.

BENIMPACT Suite is connected to databases that can be updated by developers, companies and final users in order to keep up with innovation.

Each type of evaluation belongs to a specific functional unit that can run as a stand-alone. For each design, the energetic unit performs an annual energetic dynamic simulation with hourly steps, and calculates annual energy consumption. Other functional units then calculate global energy consumption, environmental impact (Life Cycle Assessment) and costs (Life Cycle Costing) for the entire life cycle of the building.

Thermodynamic performances are verified using a package composed of "Energy Plus" and some features implemented by EnginSoft

. Environmental impact and costs are calculated using specific routines implemented by EnginSoft.

The calculation of the whole environmental impacts is performed by using the IBO database (IBO - Austrian Institute for Healthy and Ecological Building) according to the "IBO-Guidelines to calculate the OI3 indicators for buildings", but without limiting the maximum value of this parameter to 100. The OI3 indicator is calculated also for heating and cooling energy and not only for building construction elements, in order to perform a more comprehensive calculation.

A routine is available to evaluate cost performance, but since prices are strongly influenced by the local market and the amount of purchased goods, the cost database has to be supplied by the user.

The multi-objective optimization is based on a genetic algorithm which searches for the "Pareto Frontier", which collects the best solutions and represents the ideal limit beyond which every further implementation compromises the system. It is currently running on modeFRONTIER, a multidisciplinary and multi-objective software, which is also used to integrate the different functional units.

2.2 Validation of BENIMPACT Suite: case study selection

In order to test the project validity, BENIMPACT Suite was applied to different case studies, both new buildings and energy retrofitting. The validation test was made on two buildings where the monitoring data was available. Due to the fact that the use of monitored data is the most accurate way of testing strength and weakness of a software/tool, the availability of such data was the main criterion used for the selection of case studies.

The first case study was Palazzo Kofler (BZ, Italy), built at the beginning of the 20th century, retrofitted with the ClimateHouse standard and subjected to monitoring for two years. The second case study was a new building, CasaZeroEnergy in Felettano (UD, Italy), monitored in the last 12 months.

Following, the validation of the model performed on CasaZeroEnergy will be explained.

This methodology was divided into several steps:

1. Analysis of the local climate,
2. Analysis of the main building features,
3. Decision on which monitored data are important for the analysis and validation of thermal behaviour prediction,
4. Analysis of the energetic behaviour of the real building through chosen monitored data,

5. Building model construction,
6. Dynamic energy simulation,
7. Comparison of energy simulation results and monitored values,
8. LCA using BENIMPACT Suite,
9. Comparison of LCA results and values calculated by using SimaPro.

3. CasaZeroEnergy

"CasaZeroEnergy" is a detached house, concluded in 2010. It was designed according to the principles of bio-climatic architecture (Fig. 1). This means that every building element was designed in order to minimize environmental impacts, using eco-friendly materials, reducing losses and maximizing free gains from the context, using passive design strategies, both for heating and cooling.

Fig. 1 – View of "CasaZeroEnergy" in Felettano, Udine – Italy.

3.1 Local climate

The house site is characterized by a mild and humid continental climate with an average annual temperature of 13°C. There is no dry season, and summer months are quite hot. Prevalent wind runs from north to south and is useful for passive cooling (Fig. 2).

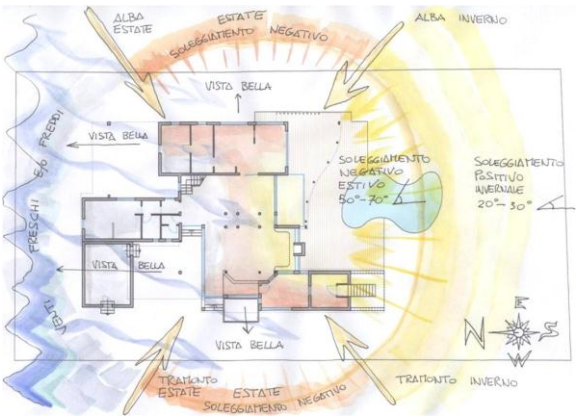


Fig. 2 – Bioclimatic concept of "CasaZeroEnergy" in Felettano, Udine – Italy.

3.2 Building shape

The building has a compact shape, with a reduced Surface/Volume ratio of 0.78, in order to minimize winter heat losses. The main facade of the building is south - south-west oriented to benefit from the apparent sun path in winter (Fig. 2). On the south facade a great sunspace is, with a glazed surface of 3.60 x 6.30 m^2. Openings on the east and west sides are protected from the summer sunshine with a system of shading achieved by moving louvers.

The building has two roofs. The biggest one, sloping, north facing, protects the house from cold winds in winter. The second one, on the south, is flat, lower than the other one, and arranged to bring photovoltaic panels. The windows on the south facade, above the flat roof, have the function to allow air movement for summer passive cooling, letting out the air entered from the opposite northern side.

3.3 Building envelope and structure materials

The building was built with renewable, recycled and recyclable materials with low embodied energy content and carbon dioxide emissions during the construction phase. For example, the hardscapes are realized with bricks and stone slabs from the demolition of old buildings within 50 km, to contain pollution from transport.

Also the structure is very low impacting, thanks to the choice of using wood as the main structural material. The walls are light-weight structures, made by a timber-frame system with wooden posts and beams. The gap insulation between the pillars

is in wood fibre, while the external insulation layer, aimed to reduce thermal bridges, is in cork. In this way the walls U-value was reduced to 0.218 W/m²K. Also the roof U-value is very low and equal to 0.205 W/m²K. Inner walls are made with wood studs and plasterboard finishing. Windows and glazed parts have a U-value of 1.3 W/m²K and 1.1 W/m²K respectively.

3.4 Passive systems and renewable energy

One of the main features of this building is that it is not connected to the gas network and it works only by using electricity, totally produced by a photovoltaic plant of 108.9 m², 13.4% efficiency and 14.6 kW of pick. Other alternative energy systems are installed in the building. The first one is the sunspace on the south facade, which allows the incoming solar radiation to be conveniently stored. The external glazes of this system are fully openable to regulate the temperature both in summer and winter.

In CasaZeroEnergy, exhausted air is naturally replaced through the openings on the north and south facades. In this way it is possible to ensure a good indoor environmental quality, the day-time cooling of the living space and the night-time cooling of the building elements. Shading systems are very important to avoid overheating during summer. For this reason these systems were properly sized and selected, in order to control and adjust the incoming heating and lighting solar radiation. Furthermore, on the building roof there is a solar collector plant of 20.91 m², 72% efficiency for DHW production.

An under-floor heating and cooling system is connected to a geothermal heat-pump that exploits the constant temperature of the earth at the deep of 2.5 m under the garden surface. The resulting nominal energy efficiency performance for heating and cooling mode are respectively a COP of 3 and an EER of 2.6.

3.5 Monitoring data

During the monitoring period, temperatures and electricity were measured respectively by sensors and multi-meters in twelve different rooms of the house. These spaces were selected because of their different exposition and final use (bedrooms, living room, kitchen, bathrooms, laundry, etc.).

The main scope of the monitoring has been to understand how CasaZeroEnergy behaves and to validate the quality of this ZEB project.

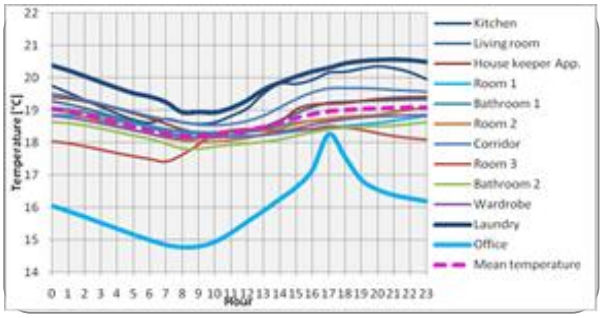
Starting from monitored data, the typical (average) day was defined both for the summer and winter period. The first one was calculated in the period between June 1st to July 31st 2011 and the second one was calculated considering the whole winter season 2011-2012 (December 21st to March 21st). Typical summer and winter days for the twelve rooms consist in 24 temperatures which are the hourly averages of the two monitored periods.

The typical winter day (Graph 1) shows that ten of the twelve monitored rooms display similar temperatures, within less than a 1.5°C difference from the average temperature. The two exceptions are the laundry and the office. Generally these rooms have a constant set-point temperature of 18°C and warmer hours depend on internal gains and solar heat gains. Causes of the different behaviour of the laundry are higher internal gains due to the presence of several pieces of equipment, which release sensible and latent heat contributions, and the windows opening during the first hours in the morning, which reduces the room temperature. The different temperature evolution in the office, however, is caused by a different set point and heating system. This space has a set point of 15°C and is heated during the day by an electric heater.

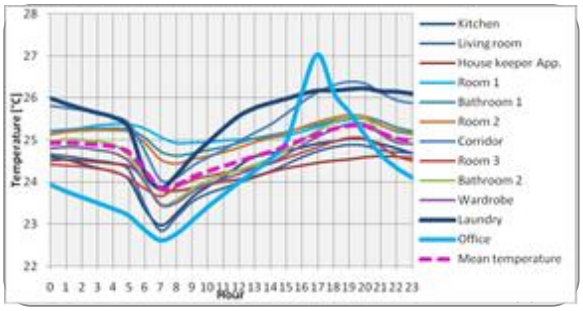
There is another important space which has not been monitored yet: the sunspace. It is very important for the passive heating of the building, because of its capacity to preheat the air and store the heat. Properly managed, the green house can be used to maximize passive solar gains from October to March, reducing the energy demand.

Also in the typical summer day (Graph 2), the same two rooms, the laundry and the office, have an inhomogeneous behaviour. The laundry is still warmer due to its higher internal gains except in the morning, when the windows are usually opened to allow the entire house to benefit from the passive cooling down effect of fresh winds from north. As in winter, the office curve presents

an odd behaviour, different from every other room. This is due to the fact that this space is not cooled. In particular it becomes overheated during the afternoon because of its west window, which has no sun protection. From the comparison of the two graphs (Graph 1 and Graph 2), it is possible to appreciate that the summer and winter behaviour of the office is similar: the two curves have an identical shape and they are just shifted along the temperature axis. This difference of temperature depends on the higher amount of solar radiation entering the room in summer.



Graph 1 – Monitored temperatures: typical winter day

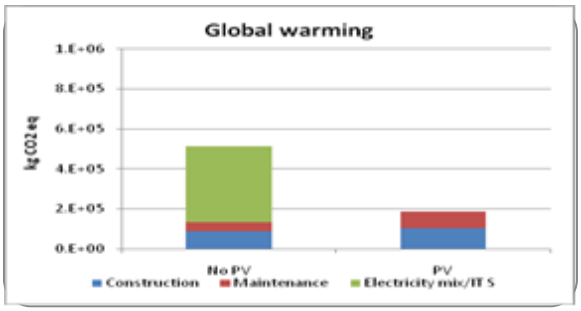


Graph 2 – Monitored temperatures: typical summer day

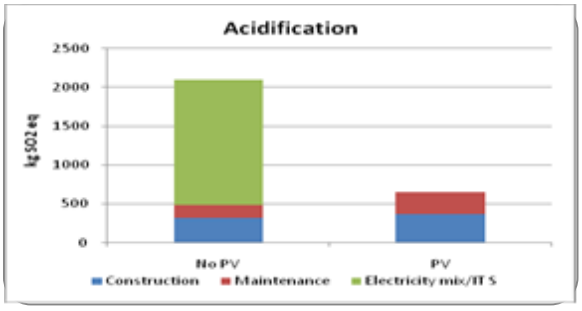
3.6 LCA with SimaPro

LCA of CasaZeroEnergy was performed by using SimaPro, one of the most complete software packages at an international level for developing environmental performance analysis. For this work the EPD (Environmental Product Declaration) method was selected as the calculation method for LCA. Because of the lack of an Italian database of materials, the assessment has been performed with EcoInvent database (CH). This database is mainly composed of European average data, and it does not consider the biotic contribution in storing carbon dioxide of wood.

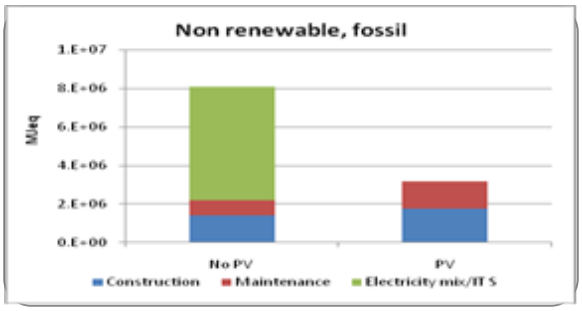
In order to perform this simulation, the life of the building was divided into three phases: construction, maintenance and use. For the construction phase every building component (external walls, floors, roofs, partitions) was modelled, omitting to consider transportation impact. Maintenance and use contributions were evaluated basing on the assumption of a building life span of 75 years. Maintenance operations were modelled taking into account the number of intervention of renovation of every single construction material. It has been estimated that the environmental impact produced by maintenance operations accounts for nearly 45% of the total. Also the contribution of the PV plant was taken into account and its convenience was evaluated through comparison with another model which works using electricity. As explained above, CasaZeroEnergy works only with electricity and that the PV plant is able to produce enough energy to cover all needs, so that no electrical energy has come from the grid. This means that, with PV panels, the usage phase does not have any further environmental impact as shown in Graph 3 ,Graph 4 and Graph 5.



Graph 3 – SimaPro: Global warming potential



Graph 4 – SimaPro: Acidification potential



Graph 5 – SimaPro: Non renewable energy

From the graphs it is possible to observe that the PV plant increases impacts for construction and maintenance, but at the same time it strongly reduces the global life cycle impact. Comparing the total impact of the house during its life cycle, it resulted that environmental loads produced by the building without PV plant are nearly the triple of the house with PV. This means that there is an effective convenience in producing energy with a PV plant.

4. BENIMPACT Suite Validation

4.1 Energy performance

The first step required to prepare an energy analysis model for a building is dividing it into thermal zones. A higher number of thermal zones affects the time required to run an energy simulation. Thus, it is important to identify the lowest number of zones able to correctly reproduce the building behaviour. Basing on the previous analysis, the model was divided into four thermal zones: sunspace, laundry, office and the rest of the house (Fig. 3).

Some hypotheses on set point temperatures, air change rates and internal heat gains were made. Set point temperature values were deduced from monitored data, while for internal gains the starting point were values given by Italian directives.

In the summer, the sunspace is open and without a heating system it is possible to better appreciate the influence of internal gains. For this reason, a model without the sunspace was prepared and verified using summer monitored data. Summer

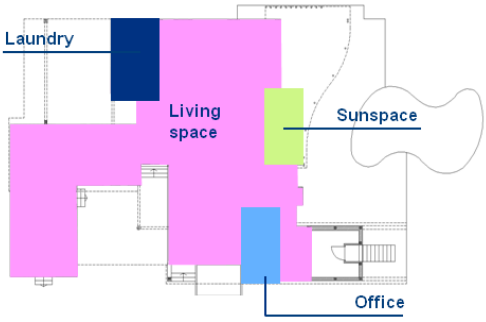


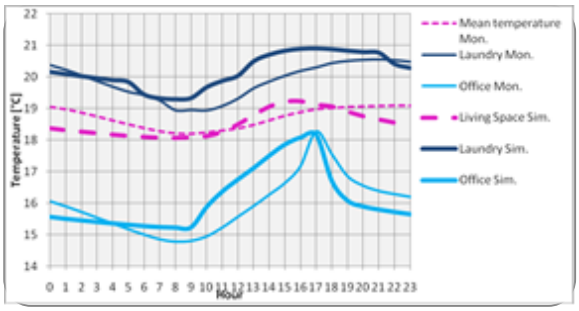
Fig. 3 – Thermal zones of the building model.

thermal simulations were run and the behaviour of the building was checked varying inputs until the model and the real building converged. At first, we also ran simulations without turning on the cooling. The living space was the easiest to adjust because it is used as a standard living space. For the laundry, increasing internal heat gains were simulated to meet the real behaviour of the room, strictly related to the presence of equipment. Windows opening, scheduled as resulted from monitoring, was then added. The introduction of this ventilation ratio was necessary for the overlapping of the model to the real building.

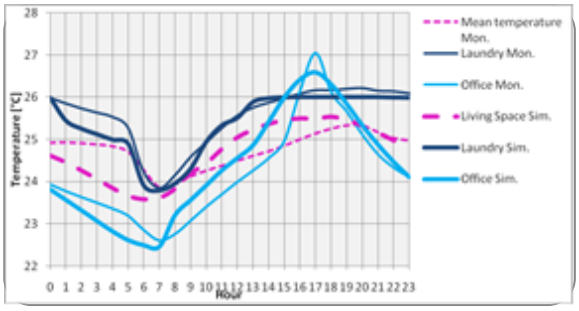
After that, the sunspace was added. In modelling this element the most difficult part was defining the air exchange rates between the living space and the sunspace and between the sunspace and the external environment. Furthermore an appropriate schedule for the sunspace opening management had to be defined, because of the lack of real data.

When the whole building model with all the four thermal zones was ready, the winter thermal simulation was verified. In order to perform this analysis, it was necessary to complete the office thermal zone definition by the introduction of a standard electric heater. The schedule of the heater was supposed looking at the monitored data.

As shown in Graph 6 and in Graph 7, the building model with four thermal zones well simulates the real temperature evolution of the building. Small differences are due to the faster response of the model, which has less internal mass, since most internal walls and the furniture are not simulated.



Graph 6 – Monitored vs. simulated temperatures: typical winter day



Graph 7 – Monitored vs. simulated temperatures: typical summer day

Thus it is possible to affirm that the required useful energy to cover the heating and cooling needs of the building, which are respectively 20 kWh/m²year and 12 kWh/m²year, can be reasonable. Moreover, those needs could be even lower than expected thanks to the higher thermal mass contribution. It is important to underline that this building is not provided with a mechanical ventilation plant with heat recovery. Therefore, the calculated energy demand is very low and the possibility to implement such a system would give greater energy results, but affecting the concept of bioclimatic architecture of the building.

As shown in Table 1, the installed PV plant covers the geothermal heat pump needs, for both heating and cooling seasons, and it also furnishes enough electric energy for home appliances and indoor lighting (Other). Moreover, 10 MWh are sold to the grid.

Another analysis was made to check the effective contribute of the sunspace to reduce the heating energy consumption. For this reason, average day useful heating power required by the living space with and without sunspace were compared and the green house contribution could be truly appreciated, reducing the useful heating energy requirements of the building by 4 kWh/m²year.

Electric Energy	Heat	Cool	Other	TOT
Consumed [kWh]	2650	1160	5000	8811
From PV plant [MWh]	-	-	-	19
To be sold [MWh]	-	-	-	10

Table 1 – Annual Electric Energy Balance by final use

4.2 LCA with BENIMPACT Suite

The LCA routine of BENIMPACT Suite can be used to easily assess the ecological impact of a building throughout its life cycle of building components and buildings: construction, maintenance and disposal.

The implemented method is based on the IBO database, using values that do not consider the biotic contribution in storing carbon dioxide of wood. Three impact index are calculated basing on the following ecological indicators:

- Global Warming Potential (GWP),
- Acidification potential (AP),
- Primary Energy Content, renewable and non-renewable (PEIe, PEIne).

A global Eco-index for the entire life of a building is also calculated. Such an index is of great importance for BENIMPACT Suite because it is used to specify the environmental impact performance when driving optimizations. This index is based on the OI_3 index and IBO formulas, but we decided to consider only positive values of the three partial eco-indicators (OI_GWP, OI_AP, OI_PEIne), and not to limit their upper value to 100. In this way we are able to easily identify environmental impacting constructions, and to take into account the primary energy contribution.

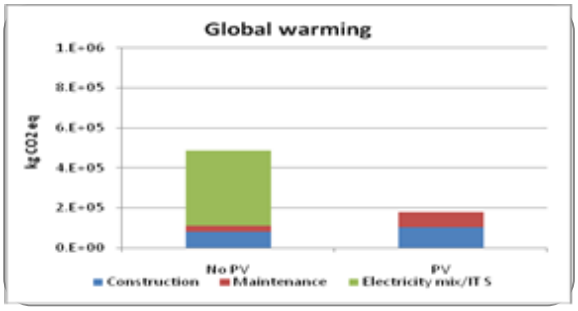
As a first step, we compared the LCA results obtained using BENIMPACT Suite to those calculated using SimaPro. We obtained smaller values using the IBO database, due to the fact that the IBO database is based on local data instead of European average values. For this reason we added new materials to our database, characterized by SimaPro impacts, replaced them in the model and re-run the LCA analysis. Results are reported in Graph 8, Graph 9, and Graph 10, which show the same behaviour as Graph 3, Graph 4 and Graph 5. Small differences depend on the

fact that in the LCA analysis ran with BENIMPACT Suite we considered only the thermal envelope of the house, without taking into account structural components. In this way the LCA routine was also validated.

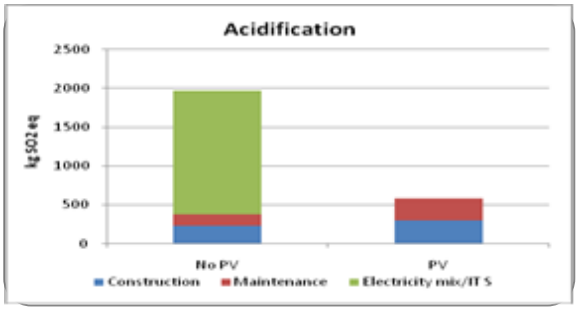
Finally, the global eco-indicator index was calculated, and results are reported in Table 2.

Global Eco-indicator	OI_3 [-]	
	No PV	PV
Construction	30	45
Maintenance	13	46
Electricity mix/IT S	302	0
Total	**345**	**91**

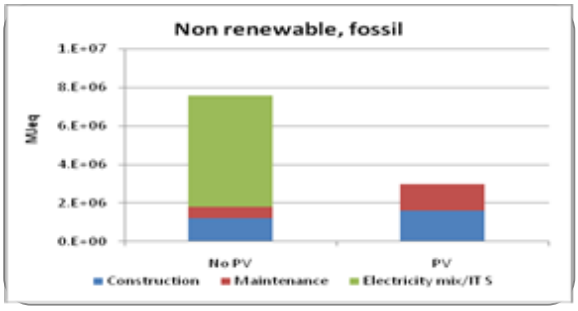
Table 2 – Global Eco-indicator with BENIMPACT Suite. PV plant effect on CasaZeroEnergy



Graph 8 – BENIMPACT: Global warming potential



Graph 9 – BENIMPACT: Acidification potential



Graph 10 – BENIMPACT: Non renewable energy

5. Conclusions

In order to spread awareness of sustainable design, "environmentally friendly" constructions must be characterized by "smart" investment, which need scientific evidence.

The test case of CasaZeroEnergy proves that BENIMPACT Suite is an effective tool to assess the energy needs and the environmental impact of a whole building, for heating/cooling plant sizing, and to verify the thermal behaviour of different rooms.

Thermodynamic and environmental performances were analyzed, hour by hour and for the entire life of the building, using the software package "Energy Plus" and some prototypes implemented by EnginSoft, showing that the specific micro-climatic condition and users habits can really affect the behave of the building or some of its rooms (see Graph 1 and Graph 2).

The validation also showed the robustness of the LCA routine implemented in BENIMPACT Suite: it works with more than one database even if results strongly depend on the input database.

6. Nomenclature

Symbols

AP	Acidification Potential [kg SO_4^{--}]
BIM	Building Information Modeling
CAE	Computer-Aided Engineering
DHW	Domestic Hot Water
EPBD	Energy Performance of Buildings Directive
EPD	Environmental Product Declaration
ErP	Energy related Products
ESD	Energy Saved Directive
EuP	Energy using Products
GWP	Global Warming Potential [kg CO_2eq.]
IBO	Austrian Institute for Healthy and Ecological Building
iDP	intelligent Digital Prototyping
LCA	Life Cycle Assessment
LCC	Life Cycle Costing
nZEB	nearly Zero Energy Building

OI_AP	Acidification Potential Eco – Indicator [-]
OI_GWP	Global Warming Potential Eco – Indicator [-]
OI_PEIne	Primary non-renewable Energy Eco – Indicator [-]
OI_3	Global Eco – Indicator [-]
PEIe	Primary renewable Energy Content [MJ]
PEIne	Primary non-renewable Energy Content [MJ]

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