# A NET ZERO ENERGY BUILDING IN ITALY: DESIGN STUDIES TO REACH THE NET ZERO ENERGY TARGET

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# ABSTRACT

The aim of this work is to model the energy consumption and the on-site production of an existing building, the Leaf House (LH), that was designed in order to be a Net Zero CO<sub>2</sub> emission home. For a more effective use of energy some of the most advanced available technologies in the field of renewable sources were used. In particular, the technological building plant includes several subsystems as a Geothermal Heat Pump (GHP), solar PV and thermal panels, integrated in a fully automatic heat distribution system. The building is only "nearly NZEB" and it is necessary to introduce some improvements in thermal plant and in energy production technological systems for reaching the NZEB goal.

# **INTRODUCTION**

To face high energy consumptions and greenhouse gases emissions of buildings, political and scientific institutions have introduced a new energy concept: the Net Zero Energy Building (NZEB) (Torcellini P. 2006). The NZEB is a building characterized by a very high energy efficiency with a total annual primary energy consumption equal to energy produced on-site (Karsten V. and Riley M. 2009; Cellura M. 2010).

The concept of NZEB is still too imprecise and the authors of this paper are involved in activities of the Sub Task B of the IEA Task 40\ECBS\Annex 52 Programme.

The task works on the definition of a common methodology to identify and refine design approaches and tools to support industry adoption of innovative demand/supply technologies for NZEBs. The above targets are pursued through detailed modeling and analysis of specific NZEB casestudies. The purpose of the detailed case studies is to provide information about the design process of

NZEBs, including parts involved and the communication between them, the decision making process, planning and the tools used. Whether or not a "forward thinking" process has been used, the case studies will also present several redesign hypothesis, which will be carefully documented. Redesign studies include changing form of buildings, technology and wall construction. It may also include a different design process or the use of a different modeling tool, such as mathematical optimization. The case studies touch all aspects of the IEA

task40/ECBCS Annex 52. They are intended to be used as a reference for others who wish to build NZEBs. One of the six case-studies of the SubTask B is the Leaf House (LH) located in Ancona, Italy (Cellura M. et al. 2011).

After a description of the main design choices and systems that led to the construction of the LH, an illustration of the monitoring and control systems and the energy output of the building has been analyzed.

A careful analysis of monitored data led the authors to search some improving strategies to reach the zero energy target. After the simulation of the real building systems, several scenarios have been investigated to improve energy performances of the LH. Finally the implemented model has been properly calibrated.

#### THE LEAF HOUSE SYSTEM

The Leaf house is located in Angeli di Rosora, Ancona, Italy;the building is south oriented (latitude  $43^{\circ}28'43.16$  N, longitude  $13^{\circ}04'03.65$  E), the altitude is 130 m. The site is characterized by a moderate climate, in detail:

- minimum annual temperature is -5°C;
- maximum annual temperature is 37°C;
- mean annual humidity is 67%;
- mean annual horizontal solar radiation is 302 W/m2.

In figure 1 the layout of the LH ground floor flat is shown. The building is composed by three levels; every one contain a couple of twin flats. The ground and the first floor flats measure  $85.39 \text{ m}^2$  each.



Figure 1 –Ground floor layout of the Leaf House Two apartments are occasionally occupied; each of the remaining four flats is occupied by two people. To maximize the solar radiation gain, the ratio of the lengths of the south and east facades was set to 1.34. For each façade the ratio of glazing area over the gross wall surface is:

- South: 23,9%;
- East: 6%;
- West: 6%;
- North 10%

The southern façade presents external fixed overhangs used as shading elements.

The house is the result of the application of new architectural design concepts dealing with the needs of comfort, sustainability, energy and economy. It was built according to the recent requirements of the energy Italian law and integrating different sources of renewable energy. The LH has a monitoring system that records the energy and environmental data of all rooms of the six apartments.

#### **Description of the envelope**

The envelope is described in the following paragraph:

<u>Walls</u>

Plaster 2 cm, Light weight brick 30 cm, Cement plastering 1,5 cm, Polystyrene 18 cm and Plaster 2cm;

<u>Roof</u>

Plasterboard 3cm, Vapor barrier0.1 cm, Wood fiber (170 kg/m<sup>3</sup>), Rock wool10 cm, sheath 0.1 cm, Air space and Pinewood2 cm;

#### <u>Floor</u>

Terracotta tiles2 cm, concrete subfloor 5 cm, polyurethane foam4 cm, Background lean concrete5 cm, Bitumen0.5 cm, Concrete 20 cm, air cavity19 cm, rock fragments11.5 cm.

Dividing floors between apartments are insulated enough (Global R value  $3.09 \text{ m}^2 \text{ °C/ W}$  in addition to the insulation of the radiating floors) to expect a negligible thermal impact of radiating floors on underneath flats.

Table 1 lists the calculated transmittance values of opaque structures.

	CALCULATED U	
EXTERNALSTRUCTURE	VALUE OF THE	
S	STRUCTURES	
	[W/(M <sup>2</sup> K)]	
VERTICAL		
STRUCTURES	0.150	
HORIZONTALFLOOR	0.300	
SLOPINGROOF	0.250	

Table 1- External structures average U values

The windows are made of a double panel insulated glazing (U=1.1 W/(m<sup>2</sup>K) with a 6 mm external glass, 14 mm gap filled with argon and4 mm internal glass; the average global window U-value is 1.40 W/m<sup>2</sup>K. The Solar Heat Gain Coefficient (SHGC) is 0.6.

#### Description of the thermal plant

In the LH the heat and cold generation is carried out by a geothermal heat pump (GHP) that exchanges with the ground through three vertical probes (100 m). In each flat of the LH there is a radiant floor supplied by the GHP. During the summer season, the cooling system uses free cooling provided by a ground coupled heat exchanger.

In the LH there is a mechanical ventilation system with heat recovery and pre-conditioning in an underground duct. The ventilation rate is automatically provided according to the  $CO_2$  levels registered in the rooms. The efficiency of the heat recovery system is 80%.

The electric energy needs of the heat pump are covered by the energy produced on site by the photovoltaic panels covering the roof facing the south.

The LH energy system includes seven sub-systems:

- The solar collector system;
- The geothermal probes;
- The heat pump;
- The air handling unit (AHU);
- The auxiliary boiler;
- The photovoltaic system;
- The radiating floors.

#### The solar collector system

Seven solar thermal collectors  $(2.6 \text{ m}^2 \text{ each})$ integrate, or completely replace (according to the season), the heat pump in the production of domestic hot water. A recirculation system allows the occupants to immediately get hot water reducing water wastes. The heat is transferred from the solar collectors to the coil of the storage tank by means of a glycol-water mixture. A pump drives the fluid back to the collectors. The difference between the outlet water temperature of the solar panels and the water inside the storage tank is less than 10 degrees; otherwise the pump is turned off (Figure 2).



Figure 2 - Scheme of the solar collector system

#### The geothermal probes and heat pump

Figure 3 represents a simplified scheme of the geothermal probes and the heat pump. The officially declared COP of the GHP is 4.6, lower than the measured value during the first year of monitoring. The efficiency reduction is probably due to:

- the non-optimal use of thermal devices;
- the anomalous electrical absorption of the compressor respect to the declared data(7-8 % higher);
- a mis-management of the ignition system characterized by too fast cycles.

The geothermal circuit, which regularly supplies the heat pump, during the summer season is connected to the free-cooling heat exchanger.



Figure 3 - Scheme of GHP system

#### The air handling unit (AHU)

As previously described, to exchange air in the rooms an AHU has been installed. Before introducing air into flats, the outer air is heated in winter and cooled in summer exchanging thermal energy with the water produced by the heat pump (Figure 4). To avoid thermal wastes, the thermal energy is extracted from the inner air before the expulsion. The outer air is also naturally pre-conditioned through an underground path of about 10 m before getting to the AHU.



Figure 4 - Scheme of the AHU

#### The auxiliary boiler

An auxiliary boiler is used to heat the fluid when the target temperature is not reached by the other systems. In figure 5 it is possible to see the position of the boiler respect to the other plants.



Figure 5 – The auxiliary boiler

#### The photovoltaic system

A grid-connected PV system characterized by a 20 kW nominal power generates electricity for the LH. The PV field , which is composed by 115 panels, covers the entire roof surface  $(150m^2)$ , facing the south. The panels are arranged in nine strings and are connected to three inverters. The nominal declared efficiency of the PV panels is 12%.

#### The radiating floors

In each flat there is a radiant floor fed by the GHP. The temperature in the rooms is controlled by a regulation system that is able to check the hot water flow through each tubing loop. Zoning valves and thermostats permit to reduce the energy consumption.During the summer season, excluding the hottest days, the cooling system uses the natural cooling provided by a ground coupled heat exchanger.

In winter, the water that circulates in the tubing has a temperature of 25-28°C.

#### Other energy efficiency measures

To pick up the natural light in the LH, wide windows face the south while in the rear part of the house facing the North the sunlight is carried by solar tubes. Furthermore, efficient fluorescent lamps are used. The rain water is collected and reused for WC and irrigation, thus reducing the water total consumptions of 69%. Drinkable water is supplied by public utility and the taps providewater through a three-way valve that supplies hot and cold water. This solution avoids to buy bottled water.

#### The control system

The monitoring and building automation system has been developed by the Loccioni Group, it uses an innovative approach based on the so called Leaf Framework. The Leaf Framework is a software platform between the system devices and the logic level which includes graphical user interfaces, building automation algorithms, business intelligence tools and databases. In other words it behaves like a software gateway between different devices and systems. More than 1,200 sensors and actuators have been integrated with drivers which allowcommunication between devices and systems by means of different protocols. The sensors are classified in three main groups: apartment sensors (CO<sub>2</sub>,air temperature and humidity sensors, electricity and thermal energy meters), mechanical plant sensors (temperature sensors, thermal energy meters, water flow meters, etc.) and weather station sensors. All data are normalized and stored in a database. The Leaf framework allows the building automation system to use all the available strategies with energy efficiency algorithms. For example the HVAC system stops if windows are open. The inlet temperature of the water in the radiant floor is regulated according to the external temperature. The air flow rate is regulated according to the CO<sub>2</sub> level in each apartment. The LH is considered as a laboratory whose stored data are analysed using business intelligence tools and used to test predictive algorithms.

#### Monitored results

In the following, the results of the first year of monitoring are presented. The design team made predictions on production and consumptions to be comparable values. As the following data confirm, they are not. The photovoltaic system produced 25,650 kWh during the monitored year. Thermal collectors provided 4,227 kWht satisfying 63% of domestic hot water needs. The electricity consumption for the heating and cooling energy provided by the GHP was 5.3 MWh during the heating season and 2.6 MWh during the cooling season. A first analysis of monitored data shows as the building is only close to reach the NZEB target.

Table 2 –Electric energy production and consumption data monitored in 2009

ENERGY	MWH	%
PRODUCTION	25.65	87.72
CONSUMPTION	30.38	100.00
PRODUCTION - CONSUMPTION	-4.73	-12.28

To increase the value of the Production/Consumption ratioit is required a redesign of the buildingequipment system: redesign hypotheses to reach the NZEB target will be described in the following paragraphs.

# LH DYNAMIC SIMULATION

To reduce the energy gap between consumption and production a dynamic model of the building and its thermal systems has been created. The model, which was built into TRNSYS (version 16.1) environment, has a complex geometry. For this reason some simplifications were assumed:

- The tank used in the production of domestic hot water was not considered because of the complexity of the double tank configuration,
- Some recirculating nodes of the piping system were eliminated,

• The air treatment unit was implemented directly in the TRNBuild, so it does not appear in the TRNSYS scheme.

In the TRNBuild simulation each flat has been divided in:

- two symmetrical zones for the ground and first floor apartments (Figure 6a): Zone 1 (red area), Zone 2 (blue area);
- three symmetrical zones for the second floor flat (Figure 6b-c): Zone 1 (blue area), Zone 2 (red area) and Zone 3 (white area).

During the summer season, the solar circuit is completely by-passed by diverting valves. The fluid used to provide the cooling effect is driven to a geothermal heat exchanger that works exchanging heat directly with the ground. The GHP in the cooling mode is activated manually.

The modeled heat pump control system is set up at a temperature of  $20^{\circ}$ C of the fluid coming from the radiant floors.



Figure 6a- The thermal zones of the ground floor



Figure 6b – The thermal zones of the first floor



Figure 6c– The thermal zones of the second floor

Each zone is simulated taking into account the real orientation of the building to better assess the solar gains. The thermal exchanges due to mechanical ventilation are evaluated setting up 0.1 or 0.2 volumes/hour of ventilation, depending on day time

schedule. The  $CO_2$  sensors activate the mechanical ventilation only when the  $CO_2$  concentration is higher than the set point value while other sensors automatically stop the mechanical ventilation when windows are open.



Figure 7 -Example of themechanical ventilation rate

The thermal gains of the zones are calculated through the TRNSYS "Gains" function : a detailed function that considers the number of people inside the house at all hours of the day, every day. Furthermore, different activity levels for the people in the house were set up.

To obtain reliable results we have developed a data climate file containing the climate time series of 2009 collected by the LH weather station.



Figure 8 - Example of the occupancy level daily schedule for flats 1-4

#### **Results and Validation**

A comparison between the monitored and calculated data was made to validate and calibrate the TRNSYS model.

At first, the trends of the average air temperature of each thermal zone and the trends of temperature in some particular days were compared.

The results of some comparisons are showed in the following figures where it is possible to see the good correspondence between monitored and calculated data.



Figure 9 - Comparison of the average air temperature of flat 3



# Figure 10- Comparison of the average air temperature of flat 4

The average difference between monitored and simulated data is 0.8 °C for figure 9 and 0.6 °C for figure 10. The highest difference is 1.5 °C for the first graph and around 1 °C for the second one.

To study the answer of the dynamic model, the temperature trends in particular days were analyzed.  $\Sigma_{\rm exc}$ 

Four days have been chosen:

- 24th January (Cloudy cold ),
- 6th March (Sunny cold),
- 24th July (Sunny hot),
- 4th August (Cloudy hot).

The average temperature of the air in all thermal zones of the LH has been calculated, as well as the PV production. Figure 11 describes the air temperature calculated in different thermal zones during  $24^{\text{th}}$  July. Also the Load Match Index has been considered when evaluating the results.



Figure 11- Comparison between monitored and simulated air temperature data for July 24<sup>th</sup>

The average difference between simulated and monitored data is  $0.4^{\circ}$ C for the first and  $0.5^{\circ}$ C for the second graph, while the maximum difference is respectively around 1°C and 1.4°C.

In Figure 12 some energy data are compared.



Figure 12 - Comparison between monitored and simulated energy production data for July 24<sup>th</sup>

The Load Match Index (LMI) is defined as the minimum value between 1 and the ratio of the electrical production and the load, it can be used to better understand how much and when the energy production of the LH is mismatching or not the energy needs.

Load Match Index = min 
$$\left[1, \frac{on - site \ generation}{Load}\right]$$

When LMI index is 1, it means that the system produces more energy than the real needs of the system. Figure 13 shows the Load Match index trend for the hot sunny day.





The monitored data in 2009 show an energy production of 25,651 kWh from the PV panels. In the TRNSYS model, the calculated production was 25,143 kWh per year.

The simulation gives a value smaller than the monitored one, with an error of 2 %.

A further validation of the model was made by comparing the monitored and simulated data of the electrical needs of the GHP .The simulated data for the heating season is about 4.7 MWh while the simulated cooling consumption is 2.7 MWh. Comparing with monitored value of 7.9 MWh/year, there is an error of about 6%. These data are close enough to claim that the simulation results are acceptable. Being sure that the implemented model well described the conditions of the LH the yearly thermal demand for cooling and heating for each apartment was assessed. In detail the results of the simulation are:

Cooling demands: 12.7 MWh/year;

Heating demands: 9 MWh/year;

# **REDESIGN**

The redesign hypothesis were made under the following conditions:

- replacement of the PV panels with different ones (19 % module efficiency, electrical features are listed in tab 3);
- replacement of the GHP with a more efficient model;
- elimination of the GHP heat exchanger and consequent direct connection of the fluid heated\cooled with the main pipeline;
- modification of the composition of the roof to reach a lower U value (0.15) W/m<sup>2</sup>°C;
- combination of hypothesis 1,2 and 3.

The redesign options have been selected trying to reduce consumptions and to increase the energy production. The Heat pump, as presented by the designers, had a 4.6 COP but monitored data showed a much lower value. This is a source of inefficiency and we tried to estimate the magnitude of these energy losses. The elimination of the heat pump heat exchanger tries to estimate the weight of one element of complexity of the thermal plant. We wanted to evaluate how much could be saved by a simpler plant in terms of electric energy. While we consider the building insulation and the quality of the envelope to be above the standards, we have performed also a simulation adding 10 cm more of rock wool in the roof composition (Global U value for the roof = 0.15  $W/m^{2}$ °C).

The simulations gave back these results:

- in the hypothesis of substitution of the PV panels with a 19 % efficiency model, the energy yield forecasted (TRNSYS simulation) would be about 38,296 kWh: this solution –would allow a complete covering of the total electrical needs of the building;
- the replacement of the GHP with a model characterized by a higher COP (4,6) would require 5.4MWh per year, comporting a reduction of 26 % (2MWh);
- the simplification of the plant would grant around 400 kWh<sub>e</sub> of savings (less than 2% of the consumptions);
- the lower U value of the roof would lead to 200kWh of electric energy savings for the winter season. However consumptions would be higher in the summer and would lead to an overall 300 kWh rise in the consumptions;
- the combination of hypothesis 1-2-3 would grant a 2.6 MWh<sub>e</sub>reduction of consumptions and a production increase of 12.65 MWh<sub>e</sub>from the PV system.

Tuble 5 T V mountes electrice jeannes				
	<b>ON-SITE</b>	REDESIGN		
PMAX [W]	175.00	240.00		
VMP [V]	36.40	43.70		
IMP [A]	4.67	5.51		
OPEN CIRCUIT V [V]	43.50	52.40		
SHORT-CIRCUIT I [A]	5.20	5.85		

 Table 3- PV modules electric features

Although the first redesign hypothesis allows the reaching of the NZEB target, options 2,3 identify significant consumption reduction: the fifth hypothesis reaches the highest value of the Production/Consumptions ratio, as it is shown in Table 4.

Table 4 – Results of the redesign hypothesis5

ENERGY	MWH	%
PRODUCTION	38.30	137.87
CONSUMPTION	27.78	100.00
PRODUCTION - CONSUMPTION	+10.52	+37.87

# **CONCLUSIONS**

This paper shows the findings of the detailed analysis of the selected case study, the LH, according to the methodology framework defined by the SubTask B of the Task 40 of the IEA. The Italian case study permits to identify the strategies to improve the energy performances of the LH and reaching the NZEB target. It represents also an Italian reference for others who wish to build NZEBs in the Italian context. The ongoing case study will foresee the development of other redesign studies in the next months: we plan to deal with economic references of the proposed hypothesis and new plant schemes in order to obtain a better load-match.

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