IOP Conference Series: Materials Science and Engineering

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To cite this article: Silvia Erba *et al* 2019 *IOP Conf. Ser.: Mater. Sci. Eng.* **609** 062026

Energy consumption, thermal comfort and load match: study of a monitored nearly Zero Energy Building in Mediterranean climate

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Abstract. Several definitions of Zero Energy Buildings (ZEB) exist in literature and different implementations of the term can be found in National laws/regulations. The differences among the Member States in nomenclature and definition of the main indicators often lead to incomparable results and difficulties in transfer and diffusion of technologies across the EU. The paper aims to investigate the topic of ZEB by clarifying the meaning of nearly ZEB and Net ZEB through the application of the definitions in a case study of a high-performance building (certified Passivhaus) located in Sicily, Italy. The house fulfils the requirements of nearly ZEB, according to Italian legislation, and satisfies the Net ZEB's yearly balance between imported and exported energy. However, the use of shorter calculation time periods highlights the presence of a relatively large mismatch between the time of use and of renewable generation. Finally, the results of the thermal comfort analysis show the achievement of adaptive thermal comfort in summer thanks to the passive features of the building (mass, external thermal insulation, solar protections) and passive techniques for heat removal (night ventilation and ground exchange).

Keywords: *nearly ZEB, Net ZEB, load cover factor, monitoring, thermal comfort*

Note: all the terms defined in ISO/EN Standards or in EU Directives are written in *underlined italics* in this text.

1. Introduction

In spite of important efforts in research and application, a number of challenges remain concerning the so-called Zero Energy Building (ZEB).Various definitions are proposed in literature and are present in National legislation, which are not easily comparable [1][2][3]; data on real performance of those type of buildings are scarce, and described according to different definitions and terminology; initial cost of some ZEBs realized till now are somewhat higher than those of conventional buildings of previous generation and closing the gap towards cost-optimal regulation [4] is an ongoing effort. In this paper we attempt a schematization of the definitions of nearly ZEBs versus Net ZEBs, taking stock of recently approved EN ISO standards, and we report detailed monitoring data of a nearly ZEB, according to Italian legislation, for which we have contributed to the design of the building fabric, controls and metering equipment. The Energy Performance of Buildings Directive (EPBD) recast of 2010 introduced the definition of nearly ZEB as a building which "*has a very high energy performance… the nearly zero or low amount of energy required should be covered to a very significant extent by energy from renewable sources, including energy from renewable sources produced on-site or nearby*". In the first round of implementation till the second recast, European MS have chosen a variety of energy indicators, thresholds and requirements to describe nearly ZEBs. The use of different nomenclatures and definitions of the main indicators in the various MS may likely create a market barrier for energy saving envelope materials and components, efficient technical building systems and design strategies for new constructions and retrofits. The new set of EN-ISO standards related to building, which should be implemented in all jurisdictions, proposes well-grounded energy performance indicators that can be used to overcome this potentially relevant barrier. The indicators which the standard considers to be needed for a rational definition of nearly ZEBs are the *energy needs for heating and cooling* , the *total primary energy* use , the *non renewable primary energy* use without compensation between energy carriers and the *numerical indicator of non renewable energy use with compensation*. In Italy the DM 26 June 2015 (annex 1) defines exactly how *renewable energy* produced *on-site* can be accounted for in the calculation of the yearly *non renewable primary energy* use, namely only to contribute to the same energy carrier and only as long as the monthly energy use of that carrier is covered. The opposite situation, where all *renewable energy* generated *on-site* and exported over a year can be used to compensate (offset) energy taken from the grid over a year, coincides with some of the definitions of net ZEB [1], where "net" is intended as difference between energy used by specified building services and the *renewable energy* generated *on-site* (or between imported from the grid and exported to the grid) over a year.

2. Case study description

The case study Botticelli project [5][6] is an all-electric single-family detached house certified Passivhaus, located in the municipality of Mascalucia in Sicily, Italy. The U-shaped building is located in a residential urban context where surrounding constructions have a maximum height of two floors. It consists of one conditioned floor of 144 m^2 above the ground and one under the ground (technical and service rooms and parking space) (Figure 1). The construction presents structural concrete and masonry with external mineral wool thermal insulation. The thermal transmittance of the external walls and the roof is 0.13 W/(m^2K) while the basement has U-value equal to 0.23 W/(m^2K). The windows U-value is comprised between 0.90 and 1.10 W/(m^2K) depending on glass to frame area ratio, while the solar heat gain coefficient and the visible transmittance of glazings are 0.54 and 0.73 respectively. The envelope air tightness (n50) is lower than 0.6 volume/h.

Figure 1. Plan view of the building (left) and urban localization (right).

The high envelope performance is complemented by the local generation of *renewable energy*. This is exploited by means of photovoltaic panels and solar thermalsy means of generation of g with the research team.ower than 0.6ol thermal insulation. The thermal transmittance of the external walls and the roof isexploiting the thermal inertia of the soil. An electrical and reversible air to water heat pump provides the domestic hot water and serves the heating/cooling coil for the ventilation system and the hot water storage tank, also fed by thermal solar panels. The building is monitored for research purposes and operated by a BACS, which is controlling the external solar blinds, the mixed-mode ventilation system, the PV and thermal solar panels and the Earth-to-Air Heat Exchanger (EAHE). The house is inhabited by a family, closely collaborating with the research team.

3. Results and discussion

This section evaluates the implementation of the nearly ZEB and Net ZEB definitions and shows the results of the comfort analysis for the case study presented in section 2.

3.1 Fulfilment of nearly ZEB definition according to Italian legislation

In Italy, a nearly ZEB is defined according to DM 26/06/2015 as a building which has a better performance than a "reference (virtual) building", which is characterized by the same shape, location, orientation, function, window/wall ratio as the actual real one but has physical properties as fixed by law in the definition of the reference building. Consequently, there are no explicit fixed energy thresholds in kWh/(m^{2}y) for being classified as a nearly ZEB but it depends on a series of requirements regarding the envelope, the energy indicators and the building systems which must be verified with respect to the reference building. In addition, the Legislative Decree 28/2011 about the promotion of *renewable energy*, coherent with the Directive 2009/28/EC, describes the minimum mandatory use of *renewable energy* through the contemporary fulfilment of three requests, which are described in Table 2. Taken together, Table 1 and Table 2, presented in [7], show the verification of the requirements for the analysed case study, according to simulation results as required by law.

Table 1. Verification of the requirements for nearly ZEB about envelope, energy indicators and building systems, according to Italian legislation.

(a) DM 26 June 2015			
Indicator	**Numerical check**	**Unit**	**Description**
$H'_T < H'_{T,max}$	$0.19 < 0.55$	[W/(m^{2}K)]	Transmission heat transfer coefficient per unit of *thermal envelope area*
$A_{sol,est}/A_{sup,utile}$ $< (A_{sol,est}/A_{sup,utile})_{max}$	$0.0029 < 0.0030$	[-]	Equivalent summer solar area ($A_{sol,est}$)[1] per unit of *useful floor area ($A_{sup,utile}$)*
$EP_{H,nd} < EP_{H,nd,limit}$ $EP_{C,nd} < EP_{C,nd,limit}$ $EP_{gl,tot} < EP_{gl,tot,limit}$	$7.21 < 30.54$ $10.25 < 18.55$ $26.21 < 74.75$	[kWh/(m^{2}y)]	*Energy need for heating* *Energy need for cooling* *Total global[2] primary energy* (includes *non-renewable energy* and *renewable energy*)
$\eta_H > \eta_{H,limit}$ $\eta_W > \eta_{w,limit}$ $\eta_C > \eta_{C,limit}$	$0.72 > 0.58$ $0.90 > 0.75$ $2.09 > 1.17$	[-]	Average seasonal efficiency of the winter air conditioning system Average seasonal efficiency of the DHW system Average seasonal efficiency of the summer air conditioning system (includes moisture control)

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[1] The equivalent summer solar area is calculated in DM 26 June 2015 (appendix A) as the sum of the equivalent summer solar areas of each glazed component and it is function of the shading reduction factor, the total solar energy transmittance of the window, the fraction of the area relative to the frame, the total projected area of the glazing component and a correction factor for the incident irradiation.

[2] It includes the following services: winter air conditioning, DHW, ventilation, summer air conditioning, artificial lighting, transportation of people and things. The *Primary Energy Factors* (PEF) for electricity from the grid are: non renewable = 1.95, renewable= 0.47, total 2.42; for electricity from on-site PV are respectively 0, 1.0, 1.0; for thermal solar on-site generation are respectively 0, 1.0, 1.0.

Table 2. Verification of the requirements for nearly ZEB about renewables exploitation, according to Italian legislation.

(b) Request (Legislative Decree 3 March 2011 – Annex 3)	**Numerical check**
Cover 50% of *primary energy* for DHW through energy produced by RES (*on-site*)	share of renewable: 86.2 %
Cover 50% of *primary energy* for DHW, summer and winter air conditioning through energy produced by RES (*on–site*)	share of renewable: 93.1 %
Power of the electrical *renewable energy* systems installed P ≥ (1 / K) * S [kW]	10.22 ≥ 2.88

3.2 Fulfilment of Net ZEB

The definition of Net ZEB is still a concept not univocally defined and standardized but it depends on different factors, an important one being the period of balance of calculation (i.e. yearly, monthly, and daily). In this case study the total electric energy use, based on monitored data from September 2015 to August 2016, is equal to 6 141 kWh/year and the yearly on-site generation of energy from PV is 10 527 kWh/year, while the total energy imported from the grid is 3 736 kWh/year and the total energy exported is 8 066 kWh/year. There is no local electric energy storage. Assuming symmetric *primary energy factors* for exported and imported energy, Net ZEB balance over a year is fulfilled by this building both if it is defined at import/export level or use/generation level. However, considering shorter time period such as the monthly balance, a certain quantity of energy imported from the grid is necessary, even in the months characterized by high energy generation from PV (Figure 2). It should be noticed that the building services which create a use of 6 141 kWh/year are a larger set than the one considered by the legislation (winter air conditioning, DHW, ventilation, summer air conditioning, artificial lighting, transportation of people and things). Our metered electricity includes in addition garden irrigation and lighting and a closed-circuit television.

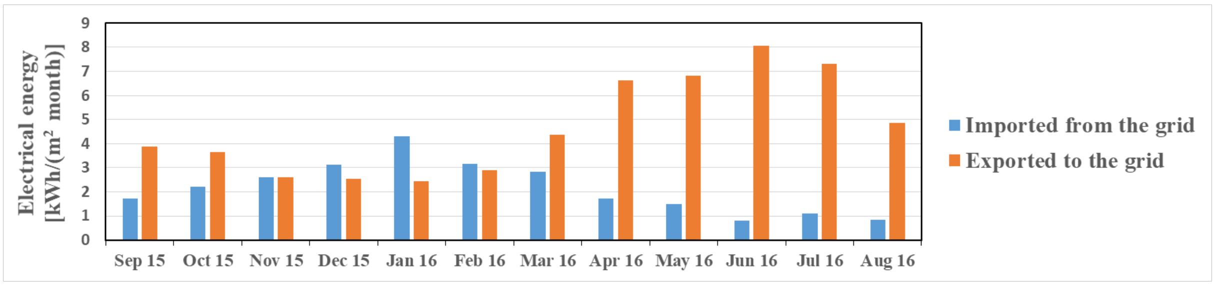

Figure 2. Comparison between the monthly electrical energy imported/exported.

To further describe the time match/mismatch between on-site renewable generation and load (energy use), we provide the calculation of the load cover factor, γ_{load}, as defined in [8], which indicates the percentage of the load covered by on-site generation.

$$\gamma_{load} = \frac{\int_{\tau_1}^{\tau_2} \min[g(t) - S(t) - \zeta(t), l(t)]dt}{\int_{\tau_1}^{\tau_2} l(t)dt}$$

Where $l(t)$ is the energy load (use), $g(t)$ the on-site generation, $S(t)$ the storage, $\zeta(t)$ the energy losses, all evaluated at time (t). In this case the terms related to energy storage and losses are equal to zero.
The value of the γ_{load} changes significantly with the considered period. The load cover factor decreases from 100 % for time resolution of a year (on a yearly basis the *renewable energy* generated *on-site* is equal or higher than energy use), to 96 % for monthly and 43 % for hourly time resolution. The building, based on measured data, hence satisfies the Net ZEB definition only when the considered time interval is a year and it doesn't on a monthly or hourly basis.

3.3 Comfort analysis

The way the comfort objectives are defined should always be the result of explicit choices which take into account both the results of high-quality comfort surveys [9], their codification in Standards (EN 15251, ASHRAE 55, ISO 7730) and the energy use associated with each comfort category [10].
When assessing a building, comfort requirements are at the present only implicitly considered, as the basis for the calculations of the energy indicators (e.g. in Italy UNI TS 11300-1 defines set points at 20 °C in winter and 26 °C in summer), but there might be scope for including them explicitly into the ZEB definitions. Figure 3 illustrates the hourly indoor thermal comfort ranges in each zone of the building based on the PMV model (from November 15th to March 31st) and the adaptive model (from September 4th to October 31st and from April 1st to May 8th). The period from May 9th to September 3rd is not comprised in the analysis due to a malfunctioning of the monitoring system. The graph shows that during the warm season (and no use of the active cooling) the adaptive temperature limits for comfort category II based on EN 15251 are satisfied in all the zones.

During the winter season in the zones intensively used (master bedroom and living room), the temperature limits (19.2 to 23.6 °C) calculated using the PMV model in correspondence of the limits of comfort category II (-0.5 < PMV < +0.5) assuming clo = 1 and met = 1.2 are always respected. In the zones occupied only for a limited fraction of the time and intermittently thermally conditioned, the PMV lower limit is not met all the time. The discontinuity between the limits of category II when considering the adaptive and PMV model is a feature of the standard EN 15251, as discussed e.g. in [1].

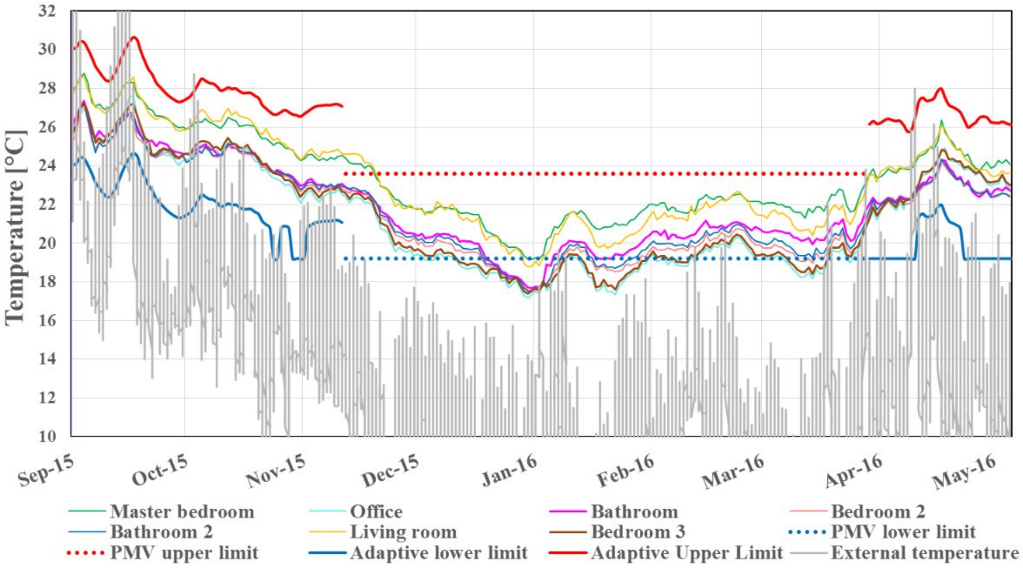

Figure 3. Hourly measured indoor temperature in each zone of the building, outdoor temperature and thermal comfort temperature limits over the period of analysis (4th Sep 2015 to 8th May 2016).

4. Conclusion

The building fulfils comfort requirements of category II in the occupied thermal zones and the Italian definition of nearly ZEB (which is based on calculated performance according to a semi-stationary monthly method). The fulfilment (based on monitored data) of the Net ZEB definition depends on the interval of analysis. If we consider a month or an hour, the cases of physical mismatch between generation and use become visible (while they are hidden when using the year as a calculation interval). These mismatches create the need for the electric grid to act as a storage of energy at short term (day-night) and at long term (summer-winter) thus transferring energy losses and capital costs to the grid. It is also questionable if the energy fed into the grid e.g. in summer, actually compensates for the energy taken from the grid in winter in terms of the associated CO_2 emissions. In case there would be many Net ZEBs, all might feed energy into the grid at the same time and all might demand energy at the same time, so no actual reduction in emissions would take place. We would hence favour the adoption of ZEB definitions which (using for the energy balance a monthly or shorter time step, as e.g. the nearly ZEB implementation in Italy), explicitly assess the needs for energy storage of a building; this might be the basis of an analysis on how best address those needs (at building, district or regional scale). The next step of research will be to explore all the possibilities for shifting (on a daily basis) part of use of energy to hours where PV generation takes place, in order to reduce the daily mismatch, even without installation of electrical storage. Long term, inter-seasonal storage (e.g. storing for use in winter the energy generated by renewables in summer) remains a challenge both in terms of available space and cost, possibly to be addressed at district scale.

Acknowledgments

The authors gratefully acknowledge Ing. Carmelo Sapienza of Sapienza&Partners engineering firm for the collaboration and the technical support. The study was partially developed within the framework of the projects A-ZEB (Affordable Zero Energy Buildings) and QUANTUM, European Union’s Horizon 2020 under grant agreements No 754174 and No 680529 respectively.

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