A Way To Net Zero Energy Buildings For Italy: How The Earth-To-Air Heat Exchanger Could Contribute To Reach The Target In Warm Climates

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Abstract

The recast of the Directive on energy performance of buildings introduces nearly zero-energy buildings. In this paper we discuss about what the expression "zero-energy building" could mean and how an existing *Passivhaus* might be improved to reach the zero-energy target in Italy, and to achieve satisfactory thermal comfort levels in summer in accordance to the norm EN 15251.

A feasible way for this optimization was identified in the installation of an earth-to-air heat exchanger. Its contribution is rather limited during winter, if it is coupled to a high efficient heat recovery unit, while it becomes a solution of primary importance to reduce, or even neutralize, the energy required to reach summer comfort.

1. Introduction

On 19th May 2010, the European Parliament and the Council of the European Union have adopted the Directive 2010/31/EU on energy performance of buildings - recast (EPBD-r). According to it, Member States shall ensure that by 31st December 2020 all new buildings are "nearly zero-energy buildings" and after 31st December 2018, new buildings occupied and owned by public authorities are "nearly zero-energy buildings" [1].

"Nearly zero-energy building" is a building that has a very high energy performance […]. The nearly zero or very 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 [1]; where "energy performance of a building" means the calculated or measured amount of energy needed to meet the energy demand associated with a typical use of the building, which includes, *inter alia*, energy used for heating, cooling, ventilation, hot water and lighting [1].

The EPBD-r entrusts Member States to set of minimum energy performance requirements in order to achieve cost-optimal balance. This means that, nowadays, reference values for "nearly zero-energy" or "very low amount of energy" are not available and they could change over time.

In this paper, we discuss how a viable energy concept for a very low energy building in northern Italy could be drafted. This implies to clarify, at least, two issues: (1) how it is possible to explicit and quantify the concept of "nearly zero-energy building", (2) in which way it is possible to reach that target for northern Italy, applied to a single-family residential building.

In order to test a design of a zero-energy building in the South of Europe, an Italian case study is presented. We have monitored a household located in *Pianura Padana*, certified to the *Passivhaus* standard, and its earth-to-air heat exchanger (EAHE) for 18 months.

2. Methodology

One of the first attempts to define the expression "net zero-energy building" was carried by Torcellini et al. [2]. They discussed and compared many potential definitions, where the neutralization of the annual balance is based on various indicators: delivered energy, primary energy, carbon dioxide emissions, energy costs. [3, 4] proposed other definitions based on carbon dioxide emissions.

The issue of defining a possibly unique or, at least, widely accepted definition is becoming increasingly important. Subtask A of the IEA Task 40 Annex 52 is working towards a proposal for an international definition for "Net Zero Energy Solar Building (NZESB)".

In this paper, we referred to the definition of "net zero source energy building" [2], since the Task 40 definition is not yet finalised. A "net zero source energy building" is a building that produces at least as much energy as it uses in a year, when accounted for at the source. Source energy refers to the primary energy used to generate and deliver the energy to the site. To calculate a building's total source energy, imported and exported energy are multiplied by the appropriate site-to-source conversion multipliers [2].

According to the IEA Task 40 Annex 52, the first strategy is to reduce energy demand through suitable architectural design and improved building envelopes. Measures for achieving this depend on climate and building type and include insulation, improved glazing and daylighting, airtight building envelopes and natural ventilation as well as active or passive shading for control of solar gains. Improving the efficiency of energy systems and services through better heating, cooling and ventilation systems, controls and lighting is the corresponding strategy for efficient use of the energy supplied [5].

In this context, a promising way to reach the zero-energy target is represented by the *Passivhaus* experience that showed, with over 8 000 realizations in Central Europe, the concrete feasibility of considerably reducing energy consumption for heating [6], while increasing the levels of thermal comfort [7] Starting for this concept optimized for heating performance, the summer energy and comfort performance could be optimized by considering the European Standard EN 15251 [13] and the extended Passivhaus Standard adapted to the Mediterranean climate [8]. To reduce as much as possible the energy needs for heating and cooling the earth heat capacity may be, in general, used like a natural energy source for example by means of an EAHE. Its contribution to the energy balance of the building was calculated, and finally, after the construction of the building, its performance was compared to metered data. In this paper we report, in particular, the result of the monitoring phase and the contribution of the EAHE to reach the zero-energy target.

3. The case study

The case study, located in Cherasco (CN), was built in 2005 and it represents an interesting combination example of passive design and the Italian building tradition[1]. The residential building has

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[1] Both for the materials used (wood for roof and horizontal structures and solid bricks for vertical structures) and for some architectural details (projecting brick, Venetian blinds and circular skylight).

two floors with a net floor area of 200 m^2. The underground floor (used as a garage and tavern), is unheated and located outside the high performance thermal insulation envelope. The Surface/Volume ratio of the house is equal to 0,54 m^2/m^3.

Fig. 1. North-West view of the case study.

The adoption of traditional structures has led to medium-high levels of effective heat capacity[2]. As for air tightness, the blower door test (conducted in accordance with EN 13829) showed a value of 0,6 h^{-1} for the parameter n_{50} (hourly air change by infiltration with a pressure difference of 50 Pa).

Planning restrictions have resulted in an North-South orientation of the main axis of the building: to ensure a better distribution of the interior spaces and offer the best view on the external environment, the main rooms and the larger glass surfaces are facing West and South. The North façade has a single window at ground floor (in the room used as office) and a skylight that provides light to the stairs. Almost all the windows can be opened.

The building is regularly occupied by a family of 4 people and, besides for housing, it is used as the seat of a small architectural study. Such use results in internal heat gains larger than those normally recorded in similar *Passivhaus*.

As for the thermal plant, following the *Passivhaus* approach, the building has a compact aggregate Aerosmart® L, comprising a cross-flow heat exchanger (composed of aluminium blades 0,1 mm thick) with nominal efficiency of 85%, an air-to-air heat pump with low thermal power (1 695 W), two fans with power of 50 W each for supply and return air, a microfiber synthetic pocket filter (class G4) and a storage tank for hot water of 200 litres. Upstream of these components is an EAHE in polypropylene (20 cm diameter , 32 m long, average depth of 2,4 m).

The air distribution system consists of two main supply ducts and two main return ducts (with tube diameter of 15 cm) and 40 m of secondary ducts (diameter 10 cm) located in the sockliner and in the partition walls. The quantity of fresh air (nominally of 205 m^3/h) is distributed in the rooms (not in the kitchen and in the bathrooms) through 9 diffusers and the extraction is carried out through 11 hygro-adjustable exhaust openings. Various types of silencers complete the plant. Taking into account the characteristics of the various components we estimated a nominal pressure drop of 800 Pa, a value in

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[2] Adopting the method of calculation proposed by the Swiss standard SIA 382/1:2007 based on ISO 13786, for the main building rooms – living room, study and bedroom – the effective heat capacity is respectively of 29, 56 and 42 Wh/K for m^2 of floor.

line with other similar realizations [9].

During the summer season, cooling loads due to solar radiation are controlled via different types of shielding elements: movable blinds with adjustable aluminum slats and roller blinds on the South and West expositions, traditional Venetian blinds on the East orientation. In addition to low-energy cooling due to the EAHE, a natural night ventilation strategy is implemented (through manual opening of some windows in the ground floor). The main features of the building are summarized in table 1.

Table 1. Summary of main features of the case study.

Quantity or Description			**Value**	
Destination of use			Residential	
Number of occupants			4	n° of person
Net floor area			200	m^2
Surface/Volume ratio			0,54	m^2/m^3
Air infiltration (n50)			0,6	h^{-1}
U-values	walls		0,15	W/(m^{2}K)
	roof		0,12	W/(m^{2}K)
	basement		0,31	W/(m^{2}K)
	center of glass		0,7	W/(m^{2}K)
Effective thermal capacity			45	Wh/(m^{2}K)
Internal gains (Installed power)			15	W/m^2
Distribution system			Air	
Nominal hourly air change (mechanical)			0,34	h^{-1}
Heating strategies	Heat recovery on exhaust air	Efficiency	85-93	%
	Heat pump	Power	1 695	W
		COP$_{nominal}$	3,6	
Cooling Strategies			Adjustable Solar Protections	
			Night Natural Ventilation	
			Earth-to-air heat exchanger (EAHE)	

4. Monitoring campaign

We installed various sensors in the building in summer 2007. Monitoring was performed from August to October 2007 and for the entire period August 2008 - October 2009. We monitored with a 10 minutes time step total electric energy consumption at the main meter and its components: consumption of the thermal plant (heat pump and fans), domestic appliances and office equipment, and lighting system. The main heat transfer flows on the thermal plant and interior micro-climatic parameters were also monitored.

In order to avoid interference with everyday activities of the occupants, we used a power line communication system, to transfer data from the sensors to the data logger. Every night data were transferred from the data logger to a server via modem on the telephone line. The long term measurement of temperature and relative humidity was carried out using stand-alone sensors-data loggers. Short-term measurements of micro-climatic parameters were conducted, in October 2007 and July 2009, using a mobile system with 3 sets of probes at different heights, according with ISO 7726 and ASHRAE RP 884 high accuracy class I protocol [10]. Consistently with available access, we evaluated the performance of the EAHE placing temperature sensors at the end of the vertical input pipe (about 50 cm deep) and in the duct connecting the EAHE with the compact aggregate. Measurements of air velocity inside the EAHE were made with a propeller anemometer (with an accuracy of 0,2 m/s).

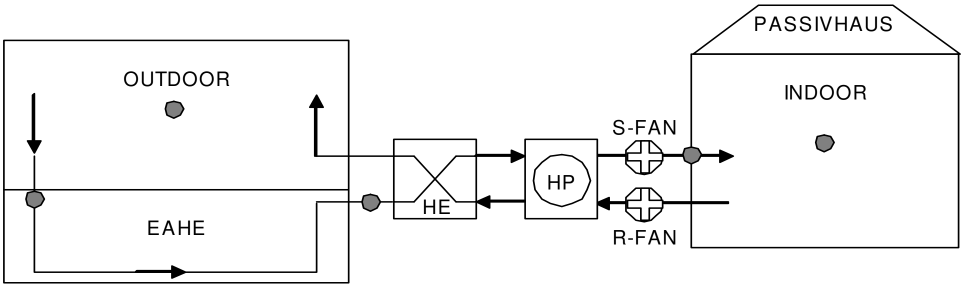

Fig. 2. Plant scheme of the case study with location of some of the sensors (gray points). EAHE: Earth Air Heat Exchanger; HE: heat recovery Heat Exchanger; HP: Heat Pump; S-FAN: Supply Fan; R-FAN: Return Fan.

To characterize the external environment during the measurement periods, we acquired the values of the main meteorological parameters (air temperature, relative humidity, precipitation, wind speed and direction), measured with hourly rate by the agricultural meteorology section of the *Regione Piemonte*.

Metered annual consumption of electric energy subdivided by end use: i) 7,6 kWh_{el}/m^2 for space heating; ii) 3,3 kWh_{el}/m^2 for ventilation; iii) 2,3 kWh_{el}/m^2 for domestic hot water; iv) 12,1 kWh_{el}/m^2 for lighting; v) 14,9 kWh_{el}/m^2 for domestic appliances and office equipment; vi) 5,0 kWh_{el}/m^2 for other uses. We calculate the overall primary energy of the building which is about 107 kWh_{pe}/m^2/year, hence complying with the limit values required by the standard *Passivhaus* (120 kWh_{pe}/m^2/year).

In order to characterize the behaviour of the EAHE, the collected data were processed (table 2) according to established methodologies proposed in the reference literature [11].

Table 2. Main characteristics and performance indicators of the monitored EAHE.

Quantity	**Monitored EAHE**
Number of ducts	1
Length of duct	32 m
Diameter of duct	200 mm
Mean depth of duct	2,4 m
Specific surface area	0,082 $m^2/(m^3/h)$
Air Velocity	2,2 m/s
Reynolds number	28800
Convection heat transfer coefficient (hc)	8,5 $W/(m^2K)$
NTU	2,1
Total pressure drop	18 Pa
Specific pressure drop: ($J = \Delta p/NTU$)	5,3 Pa
COP (heating)	262 kWh_{th}/kWh_{mec}
EER (cooling)	252 kWh_{th}/kWh_{mec}

While the convection coefficient inside the tube – function of the Nusselt number[3] and the diameter – and the NTU number well qualify the regimen of heat exchange between air and pipe wall, the parameter J (specific pressure drop) – proposed by De Paepe [12] – introduces information about the relationship of hydraulic and thermal performances. These indicators are functions only of the geometric characteristics (diameter, length and number of curves) and air flow (kept at a constant value by the plant).

Then, we can define the performance coefficients (Coefficient of Performance and Energy Efficiency Ratio) of the EAHE as the ratio between the sensible heating/cooling energy supplied to the air flow and the mechanical energy spent[4], during the reference season. Differently from the other indexes, COP and EER also depend on the regimen of heat exchange between soil and EAHE and then mainly by the depth of the tube and thermo-physical characteristics of the adjacent ground.

The maximum contribution of the EAHE to heating takes place during the coldest months, while the maximum contribution to cooling takes place in June, while the warmest months are July and August.

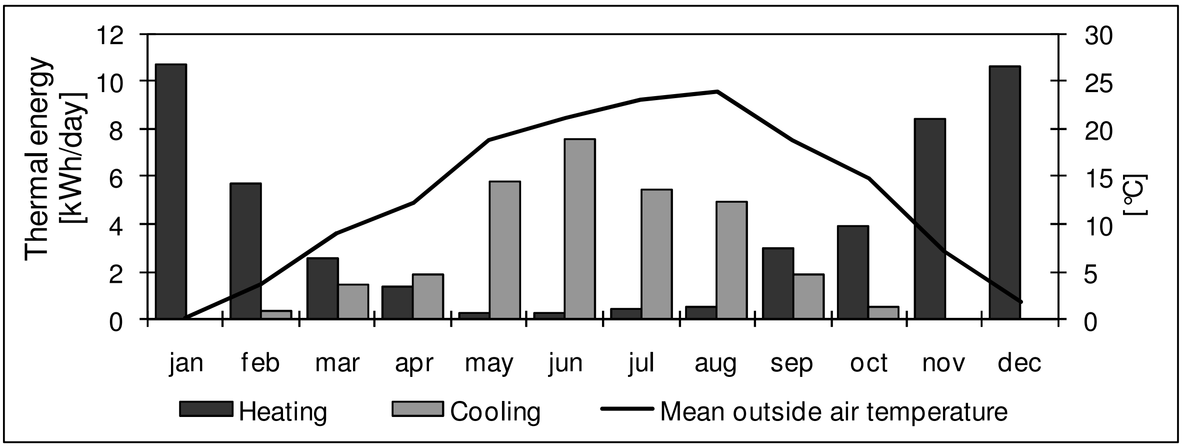

Fig. 3. Daily thermal energy supplied by the EAHE and average monthly temperature.

This behaviour is probably due to the fact that the earth is loading internal energy by the EAHE during the summer months and this imply a rise of the ground temperature. On the contrary, in winter, we note a decrease of ground temperature: at constant air flow in the EAHE, the contribution to heating in February is less than in December, even if these months are characterized by almost the same mean outside air temperature (figure 3).

The maximum heating and cooling power supplied by the EAHE are respectively 1 090 and 1 188 W. Actually the heating power supplied by the EAHE is not completely used by the building, since downstream of the EAHE there is a very efficient heat recovery unit (nominal efficiency = 85%). On the contrary the cooling power from the EAHE (in combination to solar shading, natural ventilation, high exposed thermal mass and night ventilation) is fully utilized in summer, when the heat exchanger is bypassed, and it allows to avoid the necessity of an active cooling system, guaranteeing acceptable

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[3] For the calculation of Nusselt number we use the Gnielinski's formulation.

[4] Calculated as the energy required to overcome the pressure drop.

thermal comfort conditions. The mean value of power is 3,1 W per m^2 of floor surface for heating and 3,3 W/m^2 for cooling.

4.1. Comfort evaluation

We found good levels of indoor thermal comfort from both long-period and short-period measurements. During summer the long term measurements show that (with outdoor running mean temperatures higher than 14°C) the indoor air temperatures are predominantly in the Category II comfort ranges both for Fanger[5] and Adaptive models (EN 15251 [13]) (figure 4). During winter, in one room, the temperatures were sometimes higher than the upper value of the comfort range, but they might easily be reduced through a different control of the solar protections (this remark derives from numerical simulation whose results are not reported in this paper).

From the short-period detailed measurements we could calculate the instantaneous values of Fanger PMV and evaluate the indoor comfort indexes proposed by the EN 15251 [13]. In figure 4 we show the foot-print classification: percentage of time in different comfort ranges, with reference to the comfort categories. From this elaboration and considering the acceptable deviation of 5% (in accordance with EN 15251 [13]), it is possible to assign the comfort category III, which is the target for existing buildings, to the building.

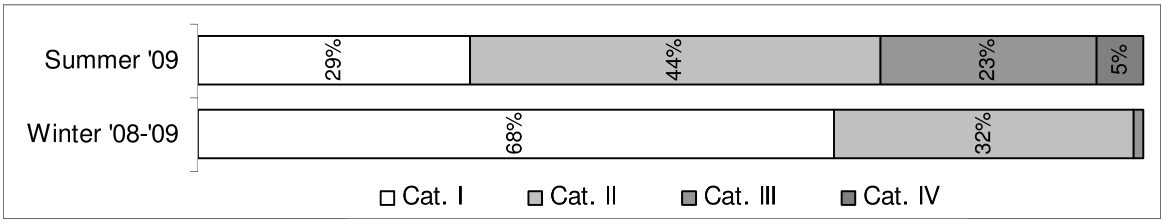

Fig. 4. Foot-print classification (% of time) from detailed comfort monitoring, based on the comfort model of Fanger (EN 15251).

5. Conclusions

In order to analyse the possibilities to reach the net zero source energy goal starting from a *Passivhaus* concept, we present the results of a monitoring campaign we conducted on a single family house located in the Po Valley and on its EAHE. Based on a 18 months metering data set, we have analized energy performance of and the power supplied by the EAHE to maximize indoor summer comfort in accordance with the standard EN 15251. Measurements and analysis performed have also contributed to European and International research projects (IEE Commoncense[6], IEA Task 40 Annex 52).

The contribution of the EAHE is rather limited during winter, if it is coupled to a high efficient heat recovery unit, while an EAHE becomes a solution of primary importance to reduce, or even neutralize, the energy required to reach summer comfort.

Applied to an existing Passivhaus, in combination with effective solar controls and natural ventilation strategies, it allows to reach the comfort target (category III) established for existing buildings by the

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[5] This theoretical range refers to the mean conditions describing the behaviour of the occupants: metabolic rate of 1,2 met and clothing resistance variable between 0,4 and 1 clo.

[6] http://commoncense.info/

standard EN 15251:2007. We found the possibility to reach the target (thermal comfort with a minimum request of external energy compensated by PV panels) replacing the use of active cooling systems with passive and very low-energy strategies, fine-tuned as function of the climatic conditions.

The delivered energy required by this building to satisfy the heating, ventilation, domestic hot water and lighting demands, is 5 060 kWh electric energy in a year (25,3 kWh/m2/y). Since this is an all-electricity building, the neutralization of the delivered energy is equivalent to the neutralization of the primary energy [2]. To compensate the delivered energy demand, almost 30 m^2 of high efficient PV panels have to be installed. In fact, assuming: (1) a slope of the PV panels of 35°, (2) that the panels are oriented to south, (3) an overall DC to AC derate factor of 0,77, an installed electric power of 5 kW is required and this implies that we need, for example, to install 17 PV panels with a nominal efficiency of 18,7% (PV modules available on the market) for a total area of 28 m^2. A further reduction of energy needs might be desirable when taking fully into account the installation cost of PV modules.

In general, these results demonstrate the feasibility of the net zero source energy approach also in the considered Italian context.

References

[1] Directive 2010/31/EU of the European Parliament and of the Council of 19 May 2010 on the energy performance of buildings (recast), Official Journal of the European Union, Vol. 53 (2010), Luxemburg.

[2] P. Torcellini, S. Pless, M. Deru, D. Crawley, Zero Energy Building: A Critical Look at the Definition, ACEEE Summer Study, Pacific Grove, California, 14-18 August 2006.

[3] Department for Communities and Local Government, Code for sustainable Homes: A step-change in sustainable home building practice, London, December 2006.

[4] Department for Communities and Local Government, Definition of zero carbon homes and non-domestic buildings, London, 17 December 2008.

[5] K. Voss, M. Riley, (2009). IEA Joint Project: Toward Net Zero Energy Solar Buildings (NZEBs), IEA Solar Heating & Cooling Programme, ECBCS Annex 52.

[6] S.R. Hastings, Breaking the "heating barrier". Learning from the first houses without conventional heating, Energy and Buildings, Vol. 36 (2004), pp 373–380.

[7] A. Schnieders, J. Hermelink, CEPHEUS results: measurements and occupants satisfaction provide evidence for Passive Houses being an option for sustainable building, Energy Policy, Vol. 34-2 (2006), pp 151–171.

[8] P. Zangheri et Al., Passive house optimization for Southern Italy based on the New Passivhaus Standard, ECEEE Summer School 2009.

[9] Wagner R., S. Beisel, A. Spieler, K. Vajen, A. (2000). Gerber. Measurement, modelling and simulation of an Earth-to-Air Heat Exchanger in Manburg (Germany), ISES Europe Solar Congress, Kopenhagen, Danemark.

[10] R.J. De Dear, G. Brager and D. Cooper (1997). Developing an Adaptive Model of Thermal Comfort and Preference, Final report ASHRAE RP-884.

[11] J. Pfafferott, Evaluation of earth-to-air heat exchangers with a standardised method to calculate energy efficiency, Energy and Buildings, Vol. 35 (2003), pp 971–983.

[12] M. De Paepe, A. Janssens. Thermo-hydraulic design of earth-air heat exchangers, Energy and Buildings, Vol. 35(2003), pp 389–397.

[13] EN 15251:2007 – Indoor environmental input parameters for design and assessment of energy performance of buildings addressing indoor air quality, thermal environment, lighting and acoustics.