Integrated design and dynamic simulation for a new zero energy building

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Abstract

The European Directive 2010/31/EU on the energy performance of buildings introduces the nearly zero-energy requirement, by 2020 and 2018 for new buildings in general and for public buildings respectively. This challenging target requires a complete assessment and optimization of the integration of efficient systems and renewable energy technologies in the building design. Dynamic energy simulation represents an essential tool in this regard.

In this context, we present an integrated approach applied to the design of a new university building in Milan, in northern Italy. This case study consists of a four-storey building dedicated to offices, laboratories and classrooms.

The building envelope design was formerly optimized, adopting passive strategies, like thermal insulation, solar control, daylighting and night natural ventilation, to reduce heating, cooling and lighting needs.

In order to meet the net zero energy requirement, locally available renewable energy sources and energy efficient systems have to be taken into account. Therefore in this case dynamic energy simulations in EnergyPlus are used to compare different heating and cooling plants options. A reference plant consists of a condensing boiler and a chiller coupled to a cooling tower, and an alternative system is based on a Ground Source Heat Pump coupled to a vertical ground heat exchanger. A VAV distribution system is assumed. Finally, PV devices are integrated in the building roof.

The simulation allows to choose the most efficient plant and to assess the overall strategy. Finally, the net zero energy target is tested and critically related to the different uses available in the building and to the climatic context.

1. Introduction

According to the European Directive 2010/31/EU on the energy performance of buildings, by 2020 all new buildings should comply with the nearly zero-energy standard. This deadline was recently put forward to the end of 2015 by the Regional Council of Lombardy, northern Italy.

The design of a Zero Energy Building (ZEB) cannot be separated from the climatic context. On the envelope design side, the ZEB concept can follow the principles of the passive and low energy building, taking advantage of the natural sinks and of the climatic drivers. On the energy supply and production design side, including RES, the ZEB concept has to take into account locally available energy technologies and sources. Therefore, ZEB examples in different European countries are needed to demonstrate the feasibility of the EPBD target.

Regarding southern Europe, some authors addressed the issue of residential ZEBs in the Mediterranean climate either analysing examples (Ferrante and Cascella, 2011; Evola et al. 2014, Cellura et al. 2014) or providing general frameworks (Oliveira et al. 2013). Yet the feasibility of the ZEB target for tertiary buildings, where internal loads and ventilation requirements can be important, still lacks in demonstration.

This paper presents the EdZEn project, namely the design of a Zero Energy multi-function university building for the Politecnico of Milan. The present study follows previous studies by the authors (Grecchi et al., 2012, Dama et al., 2014) facing the EdZen envelope design, and addresses the supply and production systems design.

Part of
Baratieri, M., Corrado, V., Gasparella, A. & Patuzzi, F. (Eds.). 2015.
Building simulation applications BSA 2015. bu,press.
https://doi.org/10.13124/9788860460745

2. Methodology

The Net Zero Energy target is chosen, namely providing through building integrated renewables the primary energy required for climatisation and lighting on a yearly basis.
The methodology is based on the following steps:

- firstly a low energy demand for heating, cooling and lighting is achieved, by means of a careful envelope design, adopting passive strategies and daylighting (Dama et al., 2014; Grecchi et al., 2012);
- secondly the HVAC systems are optimised in order to achieve high energy efficiency;
- finally RES technologies on site are adopted to provide the necessary energy.

As already mentioned, the present paper focuses on the second and third steps.
The analysis was performed by means of dynamic energy simulations carried out in EnergyPlus. In Section 3 the main characteristics of the EdZen building and its simulation model are presented. In Section 4 the two HVAC systems configuration analysed are introduced as well as the EnergyPlus models adopted for the main components. In Section 5 the results of the annual simulations are reported and discussed. Finally, in Section 6 some conclusions are provided.

3. The EdZEn building

The preliminary design of the EdZEn consists of a four-storey building dedicated to offices, laboratories and classrooms.
Offices are located on the first, second and third floor. Laboratories cover the underground area and the first and second floors of the west wing, a large classroom is located at the ground level in the east wing. The building entrance, the two wings and the south strip are connected by a central Atrium, which is not conditioned. Two views of the building rendering are shown in Fig. 1 and 2. The building is more thoroughly described in (Grecchi et al. 2012).

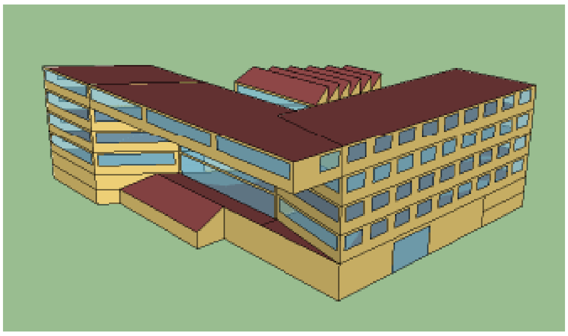

Fig. 1 – EdZEn South/East view

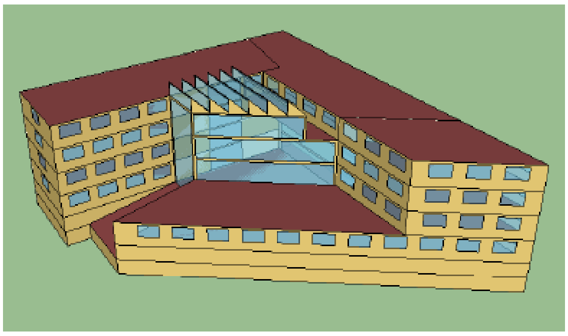

Fig. 2 – EdZEn North/West view

The building envelope components are characterised by a high level of thermal insulation and air tightness. The transparent portions are protected by external shading devices to prevent unwanted solar gains and glare effects.
A set of passive strategies for the office zones was evaluated and optimized in (Dama et al., 2014); in this work, some of those strategies are extended to the classroom and to the laboratories as can be seen in Table 1. In the office zones the lighting system uses highly efficient sources (LED) with continuous dimmer controlled by daylighting sensors.
The building was modelled in EnergyPlus (v. 8.1). 25 thermal zones were identified and simulated: 14 office zones, 3 laboratories, 1 classroom, 6 service areas (corridors, stairs and technical rooms) and 1 atrium.
Focusing on offices, classroom and laboratories internal loads due to occupancy, equipment and lighting as well as minimum outdoor ventilation rates are shown in Table 2. The minimum outdoor ventilation rates have been set according to EN 15251.

Table 1 – Passive strategies adopted in each consumer

Strategies	Offices	Classroom	Labs
Solar Control	x	X	x
Natural Night Ventilation	x		
Daylighting	x	x	
LED	x		

Table 2 – Design internal loads and ventilation rates

	Offices	Classroom	Labs
Floor area (m^2)	1133	379	1705
People (m^2/p)	10	2	20
ACH (1/h)	1.68	5.04	2.94
Equip. (W/m^2)	10		10
Lights (W/m^2)	6	12	12

4. HVAC systems

Two HVAC systems configurations were studied, differing only in the heating/cooling plants. An air distribution system was adopted for all the cases, including 5 Air Handling Units (AHU) with enthalpy recovery and Variable Air Volume (VAV) distributions, dedicated to the following groups of thermal zones:

- offices on the east wing,
- offices on the west and south wings,
- classroom,
- laboratories at ground and first floor,
- laboratories underground level.

The two configurations are:

1. Base: a Condensing Boiler (CB) for heating and a water-to-water Chiller (C) coupled with a Cooling Tower (CT) for cooling (Fig. 3);
2. Advanced: a vertical Ground Heat Exchanger (GHE) coupled to a Water-to-Water Heat Pump (HP) for winter heating and to the water-to-water Chiller (C) for summer cooling. In this case a ground Free Cooling (FC) option was also investigated (Fig. 4).

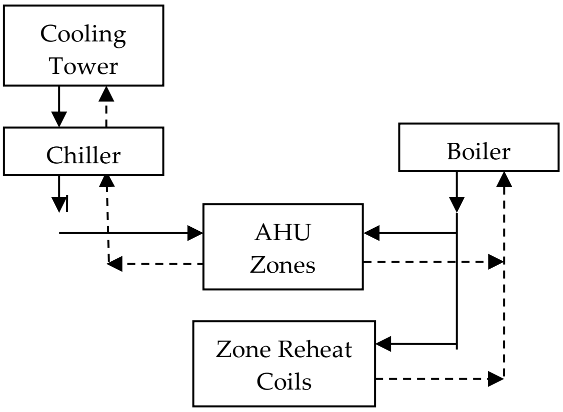

Fig. 3 – Base configuration

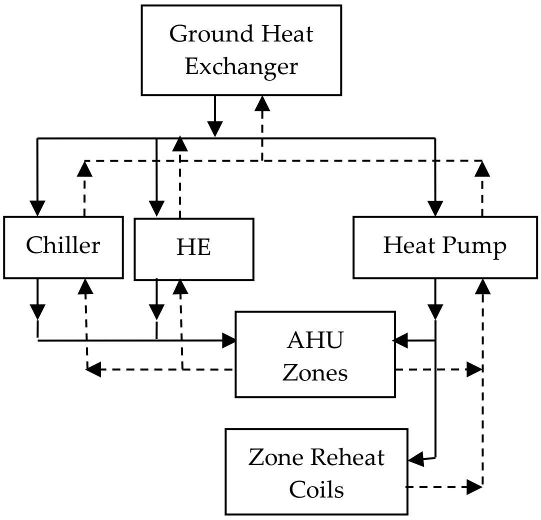

Fig. 4 – Advanced configuration

The AHU and the VAV distribution are illustrated in Fig. 5. Each AHU incorporates an enthalpy recovery system (*Heat Exchanger: AirToAir: SensibleAndLatent*) with a sensible and latent effectiveness at 100% and 75% flow rate equal to 85% and 80% respectively.

The Hear Recovery control of the classroom differs from the one employed in the other zones, which is only based on temperature differences. For the classroom, in both system configurations, the option for Indoor High Humidity (IHH) control was employed: if zone relative humidity is over 60% and the outdoor humidity ratio is below the indoor humidity ratio, then the outdoor mass flow rate increases and the heat recovery is bypassed. This option had shown significant savings in controlling high latent loads.

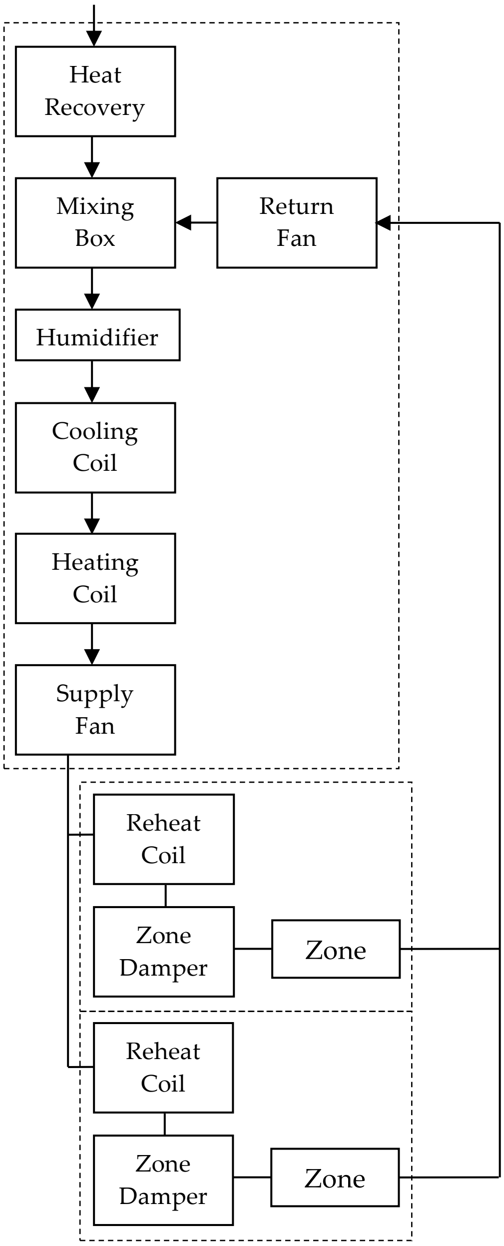

Fig. 5 – AHU and VAV

For the Gas Condensing Boiler simulation Boiler: Hot Water model in EnergyPlus was adopted. The inputs required are the boiler nominal capacity, the thermal efficiency and some performance curves. The boiler nominal capacity is 180 kW with efficiency equal to 98.4% for a water return temperature equal to 60°C. At every time step the effective thermal efficiency is calculated according to a biquadratic efficiency curve with Part Load Ratio and return temperature as independent variables.

The EnergyPlus model *Chiller: Electric EIR* was adopted for simulating the water-to-water Chiller. In this case the required inputs are the nominal cooling capacity and EER (cooling rate output to electric power input ratio) and three performance curves, allowing us to model the Chiller behavior as a function of the temperatures at the evaporator outlet and at the condenser inlet and of the Part Load Ratio. For the case study, with evaporator outlet temperature at 7°C and condenser inlet temperature at 30°C, the nominal full load capacity was 197 kW and the EER was 4.6.

A parametric model was used also for the Heat Pump, namely the *Heat Pump: Water to Water: Equation: Fit Heating*. The nominal heating capacity at 45°C condenser outlet temperature was 209 kW with a COP = 4.1 (heating rate output to electric power input ratio).

The Cooling Tower adopted in the condenser loop of the Chiller in the Base configuration is modeled as a counterflow heat exchanger with a single-speed fan by means of the *Cooling Tower: SingleSpeed* model.

The Ground Heat Exchanger was modeled by means of the *GroundHeatExchanger: Vertical model*, based on both long-term (Eskilson, 1987) and short-term (Yavuzturk and Spitler, 1999) response factors named g-functions. The borehole field was made up of a rectangular configuration of 5 x 10 U-pipes, with a distance equal to 7 m and a depth of 100 m. The ground thermal conductivity was assumed to be 2.4 W/(m.K), a typical value for a saturated sandy aquifer, and the undisturbed ground temperature was set at 14°C.

The Free Cooling option was implemented by introducing a HeatExchanger: WaterToWater, allowing us to couple directly the Ground Heat Exchanger loop with the supply loop and thus by-passing the Chiller. Free Cooling is active from October to May, whenever the GHE outlet temperature lies in the range between 14 and 16 °C. Such temperature levels are suitable for removing only sensible cooling loads. Therefore, since latent cooling load is very high and permanent in the Classroom, the Free Cooling Loop was coupled only to the AHU serving offices and laboratories.

Considering the very modest local wind velocities (the yearly average velocity is 0.9 m/s), the only renewable energy locally available is solar energy. Therefore, after choosing the most efficient HVAC configuration between the Base and the Advanced, a yearly energy balance for the three destinations, namely offices, classrooms and laboratories, was performed. Then we assumed that PV panels with a nominal efficiency equal to 17% could be placed on the EdZEn roof with a South orientation and a tilt angle equal to 30°. The PV yearly electricity generation was then calculated and compared with the energy needs of the different destinations.

The simulations were carried oud with a timestep of 15 minutes for one year, with the climatic data of Milano (Linate Airport).

The comfort set points were chosen according to standard EN 15251. In category II ($-0.5 < PMV < +0.5$), the following set points were adopted:

- Winter condition, operative temperature higher than 20°C and air relative humidity higher than 25% ;
- Summer condition, operative temperature lower than 26°C and air relative humidity lower than 60%.

5. Results and discussion

In Table 3 we show the annual specific (sensible and latent) thermal energy need for heating (ETH) and for cooling (ETC), and the annual specific electrical energy need (LENI) for lighting, for each area. The thermal power was computed from the heat exchanged on the coils, as the enthalpy difference between the air inlet on the cooling coil and the air outlet on the reheat coil.

The results in Table 4 confirm that thermal and artificial lighting demand in office zones are considerably low: this assessment was formerly given in (Dama et al., 2014) as a result of the adoption of the passive strategies listed in Table 1.

The classroom is characterised by a high occupancy level (see Table 2) which turns out in a very high specific demand for cooling and dehumidification. The energy demand in laboratories is dominated by the electric lighting, which is due to the fact that a large area is located underground.

Table 3 – Annual specific thermal energy and lighting needs

kWh/m^2	Offices	Classroom	Labs
ETH	7.4	0.0	0.9
ETC	19.5	97.1	25.7
LENI	5.5	13.6	38.2

Table 4 reports the comparison between the Base and the Advanced plant configuration in terms of annual specific primary energy consumption for heating and humidification (EPH) and for cooling and dehumidification (EPC), for each destination. Figures 6, 7 and 8 show the incidence of the use of each component.

Table 4 – Annual specific thermal energy for Base (1) and Advanced (2) configurations

kWh/m^2	Offices	Classroom	Labs
EPH-1	9.5	0	5.9
EPH-2	5.9	0	5.5
Relative difference	-38%		-7%
EPC-1	14.9	147.9	27.5
EPC-2	11.9	109.5	23.5
Relative difference	-20%	-26%	-14%

The primary energy used by boiler, chiller and heat pump was split among the destinations with the same proportion of the power exchanged on the water loops serving the corresponding AHU and reheat coils. Primary energy conversion factors assumed are 2.5 for electricity and 1.1 for gas.

Table 4 shows that the advanced solution produces a significant energy saving for the office heating. The saving potential in the laboratory heating is much lower since in this case the fan operation has a larger impact on the energy used (see Figure 8).

A considerable saving potential can be seen for cooling in all the destinations. In this comparison only a modest contribution comes from the increase of the chiller efficiency condensed with the ground water loop. Actually the major saving contribution comes from eliminating the evaporative tower and its consumption.

The comparison between the seasonal generator efficiencies is reported in Table 5.

Table 5 – Systems seasonal efficiencies in the two configurations

Base configuration		**Advanced configuration**	
Boiler efficiency	Chiller EER 1	Heat pump COP	Chiller EER 2
1.09	5.24	3.99	5.47

Figure 9 shows the dynamic profile of the Chiller EER together with the inlet water temperatures in the condenser and the Partial Load Ratio (PLR). In the considered week, the return temperature of the ground heat exchanger is 4-5 degrees below the return of the evaporative tower, resulting in an efficiency increase in the same order of magnitude of the difference in the seasonal values.

Figure 10 shows an example of free cooling operation: the GHE outlet temperature, directly sent to the Heat Exchanger, ranges between 14°C and 16°C as expected. The outlet and inlet air temperatures at the cooling coil of the offices on the south/west wing highlight when Free Cooling is exploited in those zones. On a seasonal basis the adoption of the Free Cooling strategy in the Advanced configuration results in an additional primary energy saving for cooling equal to 5% and 4% in the for offices and laboratories respectively.

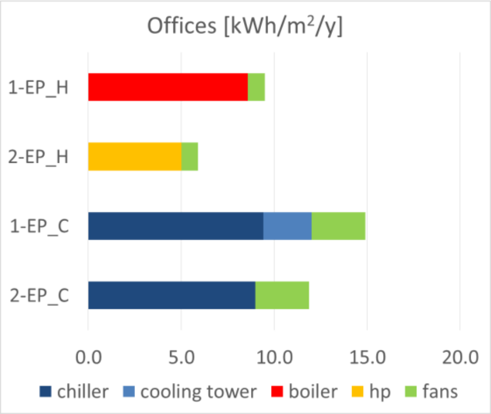

Fig. 6 – Offices: specific primary energy for cooling and for heating in the Base (1) and Advanced (2) configurations

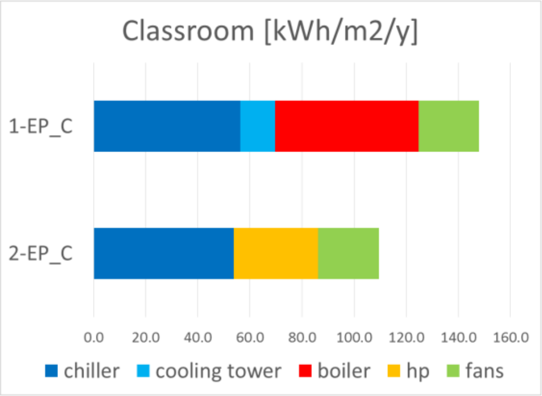

Fig. 7 – Classroom: specific primary energy for cooling and for heating in the Base (1) and Advanced (2) configurations

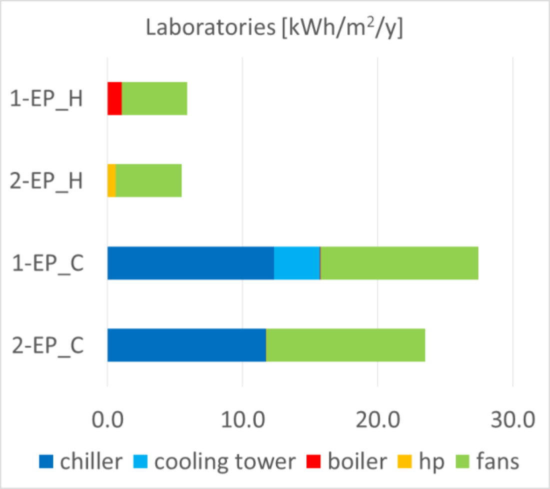

Fig. 8 – Laboratories: specific primary energy for cooling and for heating in the Base (1) and Advanced (2) configurations

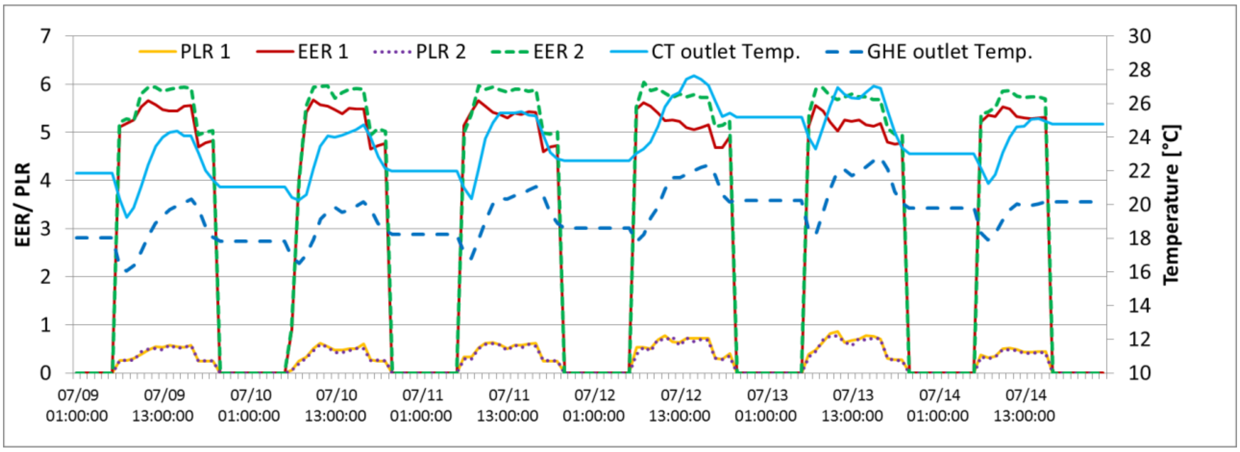

Fig. 9 – Chiller behavior in a typical summer week: EER and water temperature at condenser inlet, Base (1) and Advanced (2) configuration

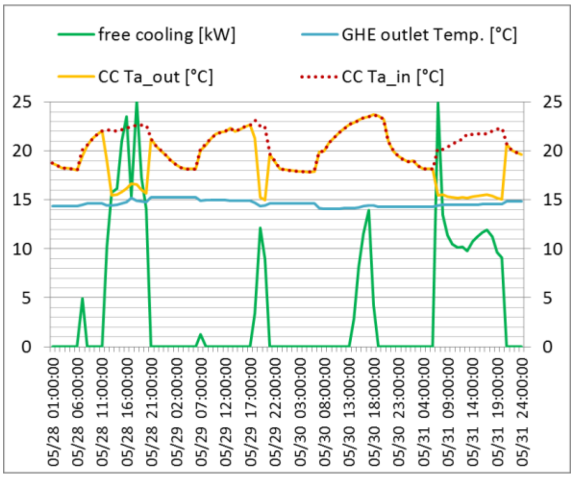

Fig. 10 – Free cooling operation in a typical summer week

In Figure 11, the annual electricity need for the three destinations is shown, together with the PV plant production. It can be noticed that, limited to offices and classroom, the Zero Energy target is almost achieved: about 95% of the energy need can be covered by the PV production on site. This outcome suggests the importance of reducing the lighting need in the laboratories, by introducing high efficiency sources (LED) and by designing proper light-shelves to convey daylighting at the underground level.

On the supply side, the possibility to adopt PV systems in the façade, integrated into the present shading systems, should be investigated.

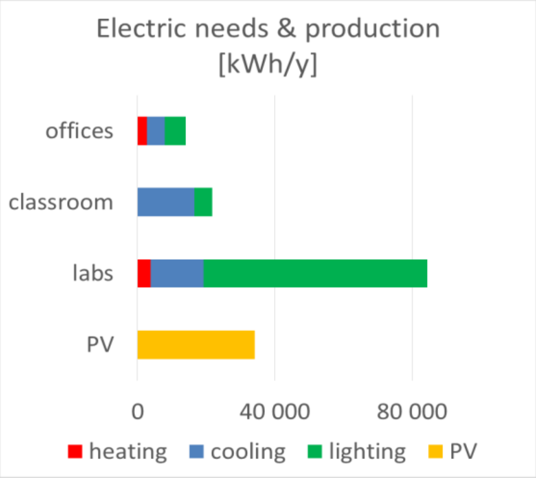

Fig. 11 – Electrical needs and PV production on a yearly basis

6. Conclusions

A comparison between two HVAC plants configurations for the EdZen building has been carried out allowing to quantify the benefits of the advanced one, which exploits the potential of the heat exchange with the ground. The building's electricity need has been broken down into the different space typologies, namely offices, classrooms and laboratories, and compared with a preliminary hypothesis for a PV production on site. Among the investigated destinations, the classroom presents the highest specific energy need, due to the high occupancy level and the consequent high ventilation rates and latent loads.

It was found that exploiting the heat exchange with the ground (Advanced configuration) results in 38% and 7% heating primary energy saving in the offices and in the laboratories respectively, and in a cooling primary energy saving ranging between 14% and 27% depending on the destination. Free cooling can provide an additional 4-5% saving. In this regard, as a future development, the possibility to adopt a mixed (air and water) distribution system will be investigated, with the aim to separate sensible and latent loads control and to better exploit Free Cooling for the sensible one.

Limited to offices and classrooms, the Zero Energy target is nearly achieved: about 95% of the energy need can be covered by the PV production on site. In this regard, adopting energy saving strategies related to lighting is crucial for achieving the zero energy goal in non-residential buildings, as the interventions adopted in the offices and in the classrooms demonstrate. Therefore, such strategies will be designed and implemented in the laboratories as well.

As a further development, on the supply side, the possibility to adopt PV systems in the façade, integrated into the present shading systems, should be investigated.

7. Nomenclature

Symbols

ACH	Air Changes per Hour
AHU	Air Handling Unit
C	Chiller
CB	Condensing Boiler
COP	Coefficient Of Performance
CT	Cooling Tower
EER	Energy Efficiency Ratio
ETH	Annual specific thermal energy for heating and humidification [kwh/m^2]
ETC	Annual specific thermal energy for cooling and dehumidification
EPH	Annual specific primary energy for heating and humidification
EPC	Annual specific primary energy for cooling and dehumidification
LENI	Lighting Energy Numeric Indicator
GHE	Ground Heat Exchanger
HVAC	Heating Ventilation Air Conditioning
PV	Photovoltaic
RES	Renewables
VAV	Variable Air Volume

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