Toward NZEB by optimizing HVAC system configuration in different climates

Available online at www.sciencedirect.com

ScienceDirect

Energy Procedia 140 (2017) 115–126

Energy Procedia

www.elsevier.com/locate/procedia

AiCARR 50th International Congress; Beyond NZEB Buildings, 10-11 May 2017, Matera, Italy

Toward NZEB by optimizing HVAC system configuration in different climates

Cristina Becchio[a,*], Stefano Paolo Corgnati[b], Michele Vio[c], Giulia Crespi[b], Leonardo Prendin[d], Micaela Ranieri[d], Davide Vidotto[b]

[a]*TEBE Research Group, Department of Regional and Urban Studies and Planning (DIST), Politecnico di Torino, Viale Mattioli 39, 10125 Torino, Italy*
[b]*TEBE Research Group, Energy Department (DENERG), Politecnico di Torino, Corso Duca degli Abruzzi 24, 10129 Torino, Italy*
[c]*RHOSS Consultant, Via delle Industrie 211, Arquà Polesine (RO) 45031, Italy*
[d]*RHOSS, Gruppo IRSAP, Via delle Industrie 211, Arquà Polesine (RO) 45031, Italy*

Abstract

Finding the most appropriate matching between envelope features and HVAC system configurations in function of different climates results fundamental for minimizing buildings' energy consumptions. The research aims at presenting the most energy-performing HVAC system configurations for high-performing buildings. Different configurations were modeled for new non-residential Reference Buildings in seven European cities, using dynamic simulation software EnergyPlus and some evaluation tools specifically set to emulate the energy performance of some specific HVAC technologies. Finally, the results obtained were compared in order to outline some conclusions, useful as guidelines for optimizing the choice of HVAC systems in function of climate conditions.

Peer-review under responsibility of the scientific committee of the AiCARR 50th International Congress; Beyond NZEB Buildings.

Keywords: NZEB; HVAC systems design; climate conditions; dynamic simulation; high-performing buildings.

* Corresponding author. Tel.: +39-011-090-4524.
E-mail address: cristina.becchio@polito.it

Peer-review under responsibility of the scientific committee of the AiCARR 50th International Congress; Beyond NZEB Buildings
10.1016/j.egypro.2017.11.128

1. Introduction

Recent concerns about the consequences of climate changes have increased the attention of politician, industry and academics on carbon dioxide emissions and their reduction. In particular, the construction industry has a significant impact on energy use and on the natural and built environment; buildings account for 40% of global energy consumption and if no action is taken to improve energy efficiency in this sector, energy demand is expected to rise by 50% by 2050 [1].

European community has set up ambitious targets for buildings to reduce emissions and energy consumptions, elements that go hand in hand. Indeed, the only way of reaching the target of 90% reduction of Greenhouse Gas emissions (compared to 1990 levels) in the building sector established by Roadmap 2050 [2] is by reducing the energy demand of buildings. This is possible with improved energy efficiency of systems, together with a wider deployment of renewable technologies.

The recast of the Directive on the Energy Performance of Buildings (EPBD) requires by the end of 2020 all new buildings to be NZEB that means buildings characterized by a very high energy performance. In the new buildings, the very low amount of required energy should be mainly covered by energy from renewable sources produced on-site or nearby. The EPBD Recast represents a turning point in designing buildings, introducing requirements based on a “whole building” approach [3]. If on one hand a single-element approach is preferred in the case of retrofit actions, on the other hand an overall performance-based approach is preferred in new constructions. Thus, in the case of new constructions, “it is fundamental to shift from an approach typically covering maximum permitted U-value only to a more extensive one including technical system requirements” [3]. Consequently, nowadays finding the most appropriate matching between envelope features and HVAC system configuration in function of the different climatic conditions results fundamental for minimizing energy consumptions.

In order to build high performing buildings, often it is fundamental to reduce the energy consumptions by improving the efficiency of HVAC systems and generators, much more than by adding a supplemental layer of insulating materials to reach even smaller U-value limits. Furthermore, NZEB concept is strongly related to a major use of renewable energy sources to cover the energy demand of the buildings. If this concept is easily achievable in the residential sector, non-residential buildings represent a greater challenge in this regard. These types of constructions consume higher amount of energy and resources with respect to residential buildings, mainly due to services that the non-residential sector must provide to the costumers. Moreover, non-residential buildings present less available space to be used to install HVAC system components that use renewable sources (i.e. PV systems and solar thermal collectors on the roof). As a result, the on-site installed renewable technologies are often insufficient in order to cover most of the energy demand, making it hard to reach NZEB ambitious targets, even if these buildings are surely high-performing ones.

The aim of this research is to present the most energy-performing HVAC system configuration for new non-residential buildings characterized by very low consumptions for different European climatic areas, using a “whole building” approach by implementing the different HVAC systems in buildings with very performing envelope features. In particular, the paper focuses on offices and hotels, since they rank among the most energy-intensive buildings in the tertiary building sector.

In detail, Reference Buildings for offices and hotels were created with two different levels of envelope thermal insulation and modeled in seven European cities characterized by various climate conditions: Rome, Milan, London, Paris, Barcelona, Berlin and Moscow. Several HVAC system configurations were defined combining different technologies for the exhaust air heat recovery to several types of chiller/heat generator and applying various distribution plant systems/terminals. Each HVAC system configuration was applied to the modeled Reference Buildings in the selected cities, in order to evaluate the effect of climatic conditions in the definition of the most energy-effective HVAC solution.

The energy-dynamic simulation software EnergyPlus was used to model the Reference Buildings and to evaluate the energy needs, while some energy-evaluation tools specifically set to emulate the energy behavior of the different HVAC technologies were used in order to assess consumptions. Finally, the results obtained were compared in order to highlight the most efficient solutions and to outline some conclusions that can be used as guidelines for optimizing the choice of HVAC systems in high-performing buildings’ design in function of climate conditions.

2. Case Studies

Reference Buildings' (RBs) aim is to characterize the energy performance of typical building categories under typical operations in the interests of generalizing the energy and financial results obtained to the whole building category [4]. Both Reference Buildings, for the office and for the hotel, are built starting from the models of the American Department of Energy (DOE) database [5] and adjusting them in order to achieve the desired features. Both Reference Buildings are located in seven different European cities: Rome, Milan, London, Paris, Barcelona, Berlin and Moscow, in order to assess the differences in terms of energy consumption as a function of the climate. The envelope of both RBs is modelled with two levels of thermal insulation: one is set in compliance with the minimum values required by regulation (Law) and the other in compliance with future values fixed for 2021 (Future).

Typical climatic conditions are taken from DOE Weather for energy Calculation Database of Climatic Data [5]. For each city, heating and cooling seasons are fixed for both Reference Buildings in compliance with regulations.

2.1. Hotel Reference Building

In the case of the hotel, the starting model is the Large Hotel post-1980 construction; it presents six storeys above ground, with a conditioned net area of 11345.29 m^2. The typical floor has an area of 1477.5 m^2 and a net floor height of 3.05 m, while first floor has major dimensions (area of 1978.8 m^2, net floor height of 3.44 m). The RB has a rectangular plant, with the major façades North- and South-oriented. A lobby, a storage, a technical room and a café for the exclusive use of guests constitutes the first floor. The model floor is completely occupied by rooms and distribution areas, while the last floor is occupied by a kitchen and two breakfast rooms, as well as by guestrooms. Totally, the hotel presents 179 rooms, of which 161 have an area of 25 m^2 and 18 an area of 39 m^2; the 20% of the rooms is empty.

All the construction typologies are selected from TABULA Webtool [6]. The sampled cities present different climates and legislations; for this reason, the construction typologies and the respective U-values differ according to the specific city. Table 1 summarizes the thermal features of the main envelope components for the two insulation levels, Law and Future.

Table 1. U-values [W/m^2K] of building envelope components.

City	Insulation Level	External Wall	External Roof	Window
Rome	Law	0.34	0.28	2.0
	Future	0.29	0.26	1.8
Milan	Law	0.30	0.25	1.8
	Future	0.26	0.22	1.4
London	Law	0.18	0.13	1.4
	Future	0.11	0.11	0.7
Paris	Law	0.24	0.23	2.7
	Future	0.11	0.10	0.8
Barcelona	Law	0.73	0.41	4.4
	Future	0.19	0.41	1.4
Berlin	Law	0.24	0.19	1.3
	Future	0.12	0.08	0.7
Moscow	Law	0.29	0.22	1.7
	Future	0.13	0.15	0.7

In the guestrooms and in the breakfast rooms, windows are equipped with internal white blinds. In the breakfast rooms, blinds are close when the zones are unoccupied. In the guestrooms, during the whole year, blinds are closed until 18:00 to prevent overheating and open in the remaining hours. In the empty guestrooms, the shading devices are always closed during the whole year.

Occupancy levels of the different zones are fixed as follows: 10 m^2/pers for guestrooms [7], 0.2 m^2/pers for lobby and café, 0.6 m^2/pers for breakfast rooms, 0 m^2/pers for the corridors and service spaces [8], while for the kitchen, the value is maintained equal to the original DOE value, equal to 5.56 people, in absence of specific European values. A typical sedentary activity of 1.2 met is assumed in all the occupied rooms, with the exception of lobby and kitchen, where a higher value is implemented, equal to 1.6 met. In terms of clothing, typical resistance values are assumed: 1 clo and 0.5 clo for winter and summer season respectively, according to EN 15251:2007 [9].

Lighting power density is fixed to 3 W/m^2 in the whole building, assuming the presence of LED systems, while equipment power densities are set equal to 4 W/m² [7] in the guestrooms while all other data are maintained from the initial DOE model. These unitary values are associated to the relative schedules, coherent for the guestrooms with ISO 18523-1 [10].

Operative temperature set points are fixed according to the comfort class I of EN 15251:2007 [9], in order to compare the results under the same conditions of thermal comfort. Set-points and set-backs assumed for heating and cooling seasons are reported in Table 2. Heating system operates during the sole heating season, while cooling is active throughout the year.

Table 2. Operative temperature set-points and set-backs and HVAC operational schedules.

	Heating set-points and schedule	Cooling set-points and schedule	Winter Cooling set-points and schedule
Guestrooms	21 / 15°C 18:00 – 09:00	25.5 / 28°C 18:00 – 09:00	25.5°C 18:00 – 09:00
Empty Guestrooms	15°C 00:00 – 24:00	28°C 00:00 – 24:00	Not active 00:00 – 24:00
Café	21°C 00:00 – 24:00	25.5°C 00:00 – 24:00	25.5°C 00:00 – 24:00
Breakfast Rooms	21 / 15°C 06:00 - 11:00	25.5°C 06:00 - 11:00	25.5°C 06:00 - 11:00
Corridors, lobby, storage, kitchen	18°C 00:00 – 24:00	25.5°C 00:00 – 24:00	25.5°C 00:00 – 24:00

The domestic hot water demand is estimated as follows, in accordance with [11]:

- 80 liters per person per day, for the bathrooms;
- 50 liters per person per day in the breakfast rooms;
- 25 liters per person per day in the bar.

The water consumption of the breakfast rooms has been divided in 6 hours instead of the 4 hours of actual service, in order to consider the dishwashing after the end of the service.

The daily requirement amounts to a total of 39960 liters. The required energy depends on the climate of the locality, because it varies with the tap water temperature. Table 3 shows the annual requirements for each city.

Table 3. Yearly required energy for domestic hot water [kWh].

Rome	Milan	London	Paris	Barcelona	Berlin	Moscow
597215	628668	660860	641337	598315	646885	665099

2.2. Office Reference Building

The selected RB is a seven-storey office building, with a conditioned net floor area of 11620 m^2. The model floor has a net area of 1660 m^2 and a net height of 2.7 m; a central core with distribution and service spaces constitutes it, while the parietal zone is entirely occupied by offices. It has a rectangular plant, with the major façades North- and South-oriented. In the models' definition, two different window-to-wall ratios are considered: 60% to simulate an almost completely glazed building and 33% to model a mainly opaque structure.

All the construction typologies are selected from TABULA Webtool [6]. As for the Reference Hotel, for the analysis, two levels of insulation are considered in order to assess different performing envelope conditions, in accordance with actual and future national legislations respectively. Table 4 summarizes the characteristics of the main envelope components and their relative U-values for the two thermal insulation levels, Law and Future.

Table 4. U-values [W/m^{2}K] of building envelope components.

City	Insulation Level	External Wall	External Roof	External Floor	Window
Rome	Law	0.33	0.29	0.32	2.0
	Future	0.17	0.17	0.16	1.30
Milan	Law	0.30	0.25	0.30	1.80
	Future	0.15	0.15	0.15	1.20
London	Law	0.18	0.13	0.13	1.40
	Future	0.11	0.11	0.11	0.68
Paris	Law	0.30	0.22	0.28	1.40
	Future	0.11	0.10	0.17	0.80
Barcelona	Law	0.73	0.41	0.50	4.40
	Future	0.19	0.41	0.20	1.44
Berlin	Law	0.28	0.20	0.35	1.30
	Future	0.12	0.08	0.12	0.70
Moscow	Law	0.29	0.22	0.19	1.70
	Future	0.11	0.09	0.10	0.90

Windows are equipped with internal venetians active only when incident solar radiation is greater than 200 W/m^2. Occupancy is fixed to 8.4 m^2/pers in all the offices [8], with the exception of the North-oriented ones, where the lower value of 16.8 m^2/pers is set. In the central core occupancy is null. Activity level is set to 0.9 met (typical sedentary activity), while clothing resistance is equal to 1 clo and 0.5 clo for winter and summer seasons respectively [9]. Lighting power density is defined as 3 W/m^2 (typical of LED systems), while equipment power densities are respectively assumed as 10 W/m^2 and 3 W/ m^2 in the offices and in the other service spaces. These unitary values are associated to the relative schedules, coherent with EN 15232 [7].

Air temperature set-points are fixed differently according to the distribution systems implemented, in order to compare the results obtained for equal thermal comfort conditions. When fan-coil and variable air volume (VAV) systems are used, set-points are set to 20°C from 7 a.m. to 8 p.m. for heating, and to 26°C from 7 a.m. to 8 p.m. for cooling. In case of radiant systems, heating set-point is 18.75°C and cooling set-point is 27.5°C, with the same time schedule. In all the models, the heating set-back of 15°C is fixed, during non-occupied hours. Heating system operates during the sole heating season, while cooling is active throughout the year. During heating season, cooling set point is fixed to 22°C for fan-coils and VAV and to 20.75°C for radiant systems. Relative humidity is fixed in a range from 40 to 60%.

3. Methodology

Some specific energy-evaluation tools were created in order to emulate the energy performance of different HVAC systems. For each building, 8 different types of systems were compared: 4 with fresh-air systems, 3 full-air VAV systems and, only for office building, 1 with radiant ceiling. The following heat recovery units were considered for each of the 8 selected system solutions (already having performances in line with ErP 2018):

- Sensitive cross flows (it cannot be modulated);
- Rotary sensitive (it can be modulated);
- Rotary enthalpy (it can be modulated);
- Rotary sensitive assisted by direct adiabatic cooling (DAC);

- All the above with or without a regenerative recovery unit, namely a run around coil (RaC) using pre- and post-heating coils [12].

Air-to-water chillers and heat pumps (HPs), in Eurovent A class, were simulated with scroll, screw and centrifugal (Turbocor) compressors.

As for the hydraulic circuits, different solutions were considered: primary and secondary circuits with constant flow rate, primary circuit with constant flow rate and secondary one with variable flow rate, primary and secondary circuits with variable flow rate.

The number of results obtained from the research is very high. Anyway, the aim of the study is not so much to give a summary of the results, but rather to identify a virtuous path to get as close as possible to nearly-zero energy HVAC systems.

3.1. Accessibility to renewable energy sources

The sun is the only renewable energy source available worldwide. Indeed, all other renewable sources (i.e. wind, hydropower, including tides, biomass, etc.) are not available everywhere and they should be considered exceptions. Often, it is difficult to install significant solar fields and it is not always available a surface properly oriented to the south to place it. Even when there is enough space, it may happen it is in the shade for long time, because surrounded by taller buildings. In any case, the lower the energy consumption is, the lower the required space will be. Consequently, it is essential to design building characterized by low energy demand and by high-efficiency HVAC systems.

3.2. Two new energy parameters: the Photovoltaic Equivalent Surface and the Proximity to Zero

In order to express easily the order of magnitude of energy consumption and to make it understandable by anyone, a comparison parameter, the so-called Photovoltaic Equivalent Surface (PVES), was identified. It can be defined as the surface of a photovoltaic (PV) array required in order to bring to zero the difference between the annual electricity self-production and the overall consumption associated to the HVAC system, including auxiliaries [13].

The PV array consists of crystalline silicon panels with 14.4% electrical efficiency, oriented to the south and with a 40% slope, so as to apply the solar electric generating estimates of the European Commission Joint Research Centre (JRC). With this performance, to obtain 1 kW_{peak} power at an irradiance of 1000 W/m^2, 7 m^2 of panels are needed.

Considering that the natural gas used by traditional boilers can produce electricity with 55% efficiency, equivalent to the best technology available nowadays, the Photovoltaic Equivalent Surface, expressed in m^2, is given by the following formula:

$$PVES = 7 \cdot P_{PVpeak} = 7 \cdot \frac{EC_{tot}+(9.6 \cdot MC_{tot} \cdot 0.55)}{SEG_{Estim}} \quad (1)$$

Where:

- 7 is the required surface to reach 1 kW_{peak} power for the reference photovoltaic panel considered (η_{el} = 14,4%), in m^2/kW_{peak};
- P_{PVpeak} is the photovoltaic peak power needed to produce all the energy required to bring to zero the difference between the electricity self-production and the total consumption of the plant, in kW_{peak};
- EC_{Tot} is the total annual electricity consumption of the plant, included the auxiliaries (pumps and fans), in kWh;
- 9.6 is the specific heat capacity of natural gas, in kWh/m^3;
- MC_{Tot} is the yearly consumption of natural gas of a boiler, in m^3;
- 0.55 is the best electrical efficiency of the currently available electricity generation system powered by natural gas;
- SEG_{Estim} is the yearly solar electricity generation estimated by JRC for 1 kW_{peak} of PV systems, in kWh/kW_{peak}. This value is equal to 1180 kWh/kW_{peak} in Rome, 1060 kWh/kW_{peak} in Milan, 952

kWh/kW$_{peak}$ in London, 976 kWh/kW$_{peak}$ in Paris, 1420 kWh/kW$_{peak}$ in Barcelona, 913 kWh/kW$_{peak}$ in Berlin and 822 kWh/kW$_{peak}$ in Moscow;

PVES allows evaluating any other source of renewable energy; the use of solar thermal energy, for example, reduces the amount of natural gas or electricity consumed by the generation systems that produce domestic hot water (boiler, Polyvalent HP or both) and, therefore, its effectiveness can be evaluated using the PVES parameter.

Although PVES can give an absolute qualitative assessment of the HVAC system, it cannot define how much this system is close to zero, because it depends on the surface and on the features of the installed photovoltaic array. For this reason, it is useful to define a second index, called Proximity to Zero:

$$PtZ = \frac{\eta_{PV} \cdot S_{PV}}{0.144 \cdot PVES} \tag{2}$$

Where:

- S_{PV} is the surface of the installed photovoltaic array, in m²;
- η_{PV} is the electrical efficiency of the installed photovoltaic array;
- PVES is the photovoltaic equivalent surface, in m²;
- 0.144 is the electrical efficiency of the reference photovoltaic array (as above explained).

PtZ can be defined either for the sole HVAC system use or for the whole building consumption. In the first case, if its value is greater than one, it means that the produced electricity is also available for supplying the other building uses. In the second case, a value greater than one indicates an annual PV production higher than the total consumption of the building.

3.3. Going downstairs to Zero-Energy

The virtuous path leading to Zero-Energy is a stair, to go down step-by-step. First, it is fundamental to avoid some mistakes. The greater of these is the regulation of the air handling unit (AHU) cold coil at a constant temperature all year long, not tied to air relative humidity (RH) value. Doing this, energy and financial losses are very high, as emphasized by [12] and [14].

Another error to avoid is the use of a heat recovery system from the exhaust air with high efficiency without power modulation. In some cases, the recovery may be by-passed too soon, with increased consumptions [12, 15].

The initial step of the analysis is a reference system with primary air and fan-coils supplied by water at fixed temperature of 7°C. A boiler for the heating and a Eurovent A Class air-to-water chiller for the cooling are used as generators. The heat recovery from exhaust air is a modulating sensible heat exchanger with 73% efficiency.

Different optimization actions are taken into account, which are analysed proceeding step-by-step.

- STEP 1: it is different from the reference system because of variable water flow on primary and secondary hydraulic circuits. On the primary circuit, dual-pumps system is always used since it is the most reliable, allowing major energy savings [16]. STEP 1 also adopts the water temperature variation when the load reduces, both in heating and in cooling.
- STEP 2: it reduces the primary air flow rate, now based on the effective presence of people in the zones.
- STEP 3: it considers other types of heat generators; boiler and chiller are replaced by one or more Polyvalent Heat Pumps.
- STEP 4: it occurs in case other types of exhaust air heat recovery (enthalpy, sensible assisted by Indirect Adiabatic Cooling) could give better results with respect to the reference system (sensible heat exchanger).
- STEP 5: it adopts a Run around Coil (RaC) system for the recovery of the post-heating in the cooling, obtained by piping in series the coils of pre-heating and post-heating.
- STEP 6: it involves the use of a Variable Air Volume system.

4. Analysis of the results

4.1. Going downstairs to Zero-Energy: Office Buildings

Figure 1 shows the virtuous path towards NZEB in the case of office buildings. The diagram on the left shows the absolute values, expressed in PVES; going from the worst to the better HVAC system, the consumptions have more than halved everywhere. The diagram on the right shows the gain of each step compared to the base solution.

The biggest advantages are obtained with STEP 3 (use of Polyvalent HPs) and STEP 6 (use of VAV systems). The VAV systems are very advantageous because they allow the exploitation of free cooling, but they require very large ducts to save energy for the fans of AHU [17]. Moreover, they are difficult to install, especially in the case of existing buildings' retrofits.

However, VAV systems give very high performances everywhere: Barcelona is an exception for its particular climate.

STEP 1 (use of hydraulic systems with variable water flow) guarantees more than 10% savings compared to the base solution. STEP 2 (variation of fresh air flow with the presence of people) gives more savings in North Europe.

The savings resulting from the use of heat recovery systems different from the sensible one are quite limited. In any case, in office buildings, the enthalpy technology is less suitable, due to the presence of endogenous latent loads. The better technology consists in the indirect adiabatic cooling system (IAC). Also in Moscow, the coolest city, the sensible heat recovery assisted by the IAC is better than the enthalpy one.

In southern European cities, it is advisable to use the RaC technology.

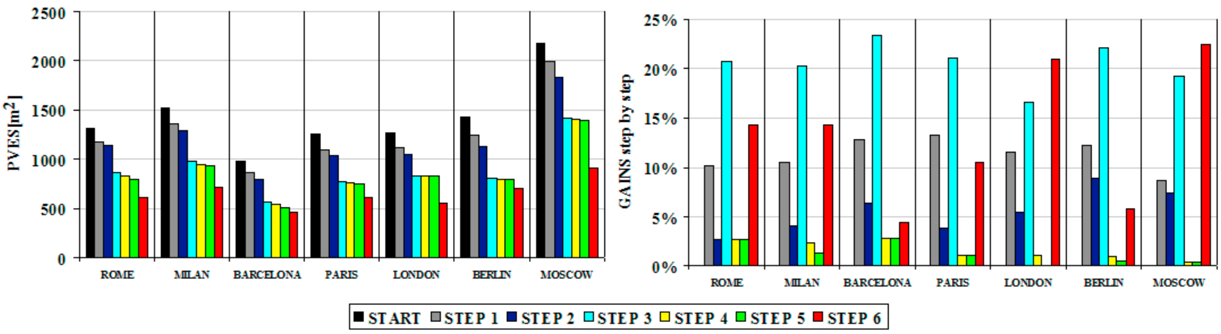

Fig. 1. Going downstairs to Zero-Energy: Office Buildings.

4.2. Going downstairs to Zero-Energy: Hotel Buildings

The same diagrams are built for hotels (Fig. 2). In this case, STEP 6 is not considered because the hotel should use VAV systems supplied by only fresh air; the power would increase considerably, even more than the energy required. Also in this case, optimizing the HVAC system more than halves the consumption.

STEP 1 (use of hydraulic systems with variable water flow) guarantees 10% savings compared to the base solution.

STEP 2 (variation of fresh air flow with the presence of people) gives a further saving varying from 17% in London up to 25% in Moscow. It must be highlighted how these savings are largely due to the lower electricity consumptions for the AHU fans, rather than for generators in southern European cities [17].

STEP 3 (use of Polyvalent HPs) is more convenient, allowing more than 30% savings everywhere, with the exception of Moscow, which still stands at a little less than 15% gain. Moscow is a very cold city, with minimum temperatures below -20°C; for many hours during the winter, especially for domestic hot water production, the heat pump may not work at all or may have an efficiency lower than that of the boiler.

The other steps relating to the different types of heat recovery from the exhaust air give little benefits, with the exception of Moscow.

It is important to emphasize that the enthalpy heat recovery gives the best results; this is due to the lower latent endogenous loads with respect to the office ones. The use of RaC is always recommended.

It should always be borne in mind that in hotels the energy expenditure for the production of domestic hot water is high; as a result, the percentage gains related to fresh air treatment become marginal. However, every little advantage helps to reduce energy consumption to reach the NZEB targets.

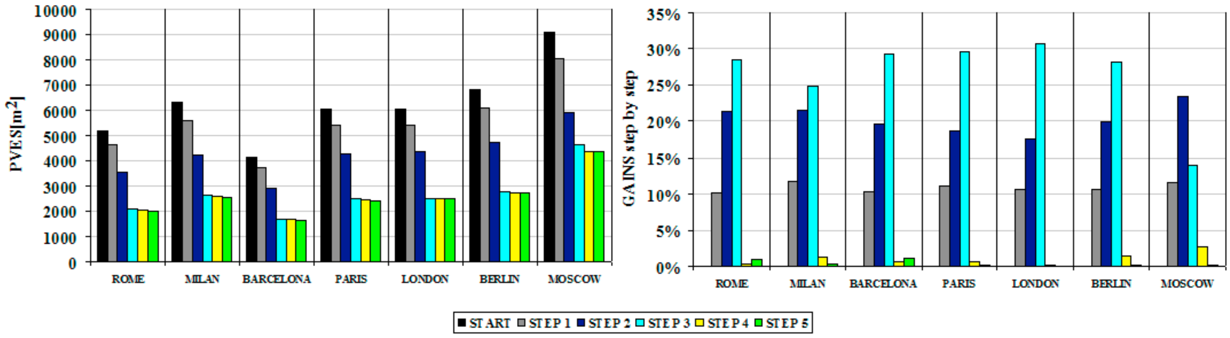

Fig. 2. Going downstairs to Zero-Energy: Hotel Buildings.

4.3. Focus on domestic hot water production

Three different systems for the production of domestic hot water were studied:

- Polyvalent HP;
- Polyvalent HP + water-to water HP equipped with R134a as a booster;
- Polyvalent HP + boiler.

The major limitation of the solution with only Polyvalent HPs is the maximum allowable temperature of the produced water; 55°C at the heat pump side, which becomes at most 52°C-53°C at the domestic hot water side, value too low to eliminate the danger of legionella bacteria. Moreover, the thermal shocks with electric heaters are not advised because extremely expensive from an energy point of view. It is possible to overcome this problem by adding a water-to-water heat pump (booster), piped on the Polyvalent HP hot water circuit, on the return pipe, that works as a cold heat source [17]. This heat pump produces all the required domestic hot water. The refrigerant R134a allows reaching water temperatures above 60°C, thus eliminating the danger of Legionnaires' disease.

Alternatively, it is possible to produce hot water up to 45°C with the heat pump and to increase the temperature up to 60°C using a boiler.

Figure 3 shows the differences between the three studied systems for all the European cities, with the exception of Moscow (where it is not possible to use a system without boiler because of the cold climate).

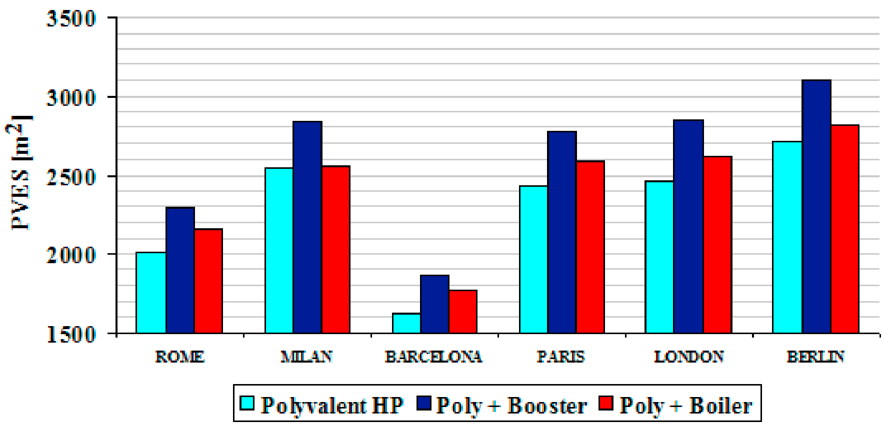

Fig. 3. Differences between domestic hot water production systems (Future insulation).

The solutions with only Polyvalent HPs are the best everywhere, followed by the solution with HP and boiler working together. This is true in buildings with Future insulation; in buildings with Law isolation, Polyvalent HP + boiler becomes the best solution in Milan, Paris, Berlin and London. This result depends on the variation of the cooling loads at low air temperatures; the cooling loads with Future insulation are higher than those with Law insulation. Therefore, Polyvalent HPs work in recovery mode for a longer period, especially with low air temperature conditions, when the operation in the sole cooling mode is energetically disadvantageous compared to the use of the boiler.

4.4. Focus on the use of solar energy: PV or thermal systems?

When domestic hot water production is needed, it is reasonable to ask if it is better to use the available space to install PV or solar thermal fields. The use of solar thermal systems reduces PVES, but it also restricts the available space for the photovoltaic array. Therefore, in these cases, it is more meaningful to use the PtZ index (Proximity to Zero) for the analysis.

Fig. 4 shows what happens in buildings with Future insulation in the various cities when the surface occupied by solar thermal systems is increased at the expense of the PV array, whereas a total of 1500 m^2 of space in the roof is present for both solar fields.

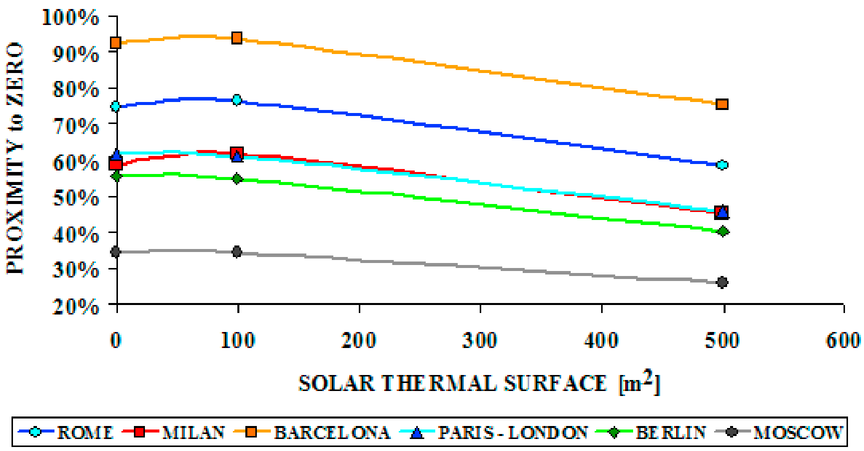

Fig. 4. Proximity to zero analysis in the different European cities.

In Southern Europe cities, it is correct to install a small solar thermal area, less than 100 m^2 (where PtZ has a slight maximum), while in Northern European cities the roof should be used only for PV array (PtZ always decreases).

This consideration is valid from an energy point of view. Indeed, from a financial standpoint, it is always better to use the space for the PV array, if the Polyvalent HPs technology is used, at least with the current electricity prices in Italy. For example, in Rome the addition of 100 m^2 of solar thermal would increase the annual electricity costs of € 11000 compared to the condition with only PV array and of even € 28000 if 500 m^2 are occupied by solar thermal systems.

4.5. Focus on thermal insulation effect

Figure 5 shows the results obtained by the best HVAC systems in the different cities examined, in function of the thermal insulation, for office buildings and hotels. Figure 6 shows the percentage gains due to the increase of thermal insulation, from Law level to Future level; negative values indicate a worsening of energy consumption in the case of Future level insulation.

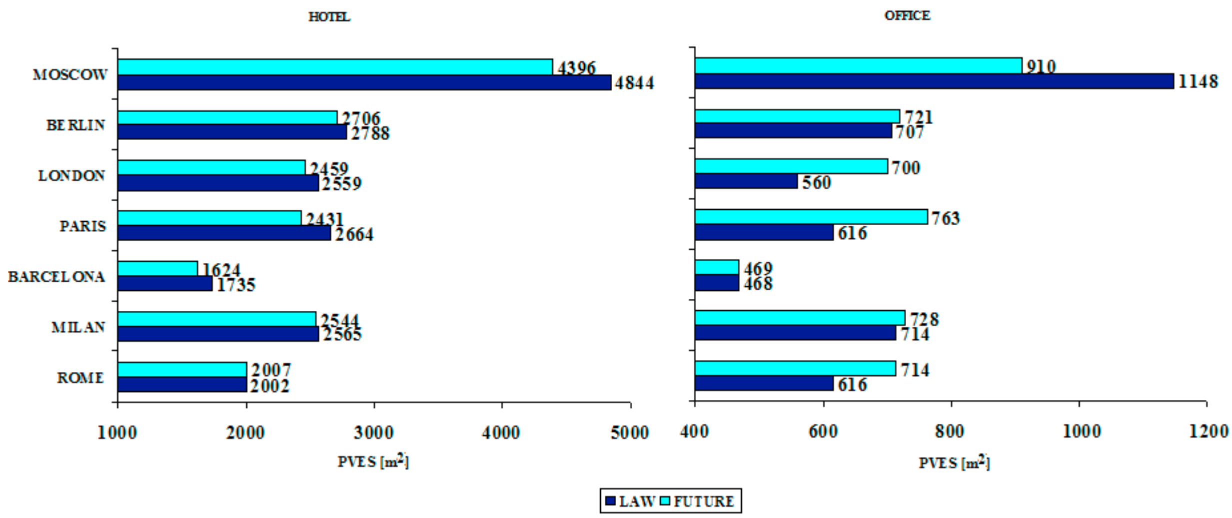

Fig. 5. Results obtained by the best HVAC systems in function of thermal insulation in different European cities.

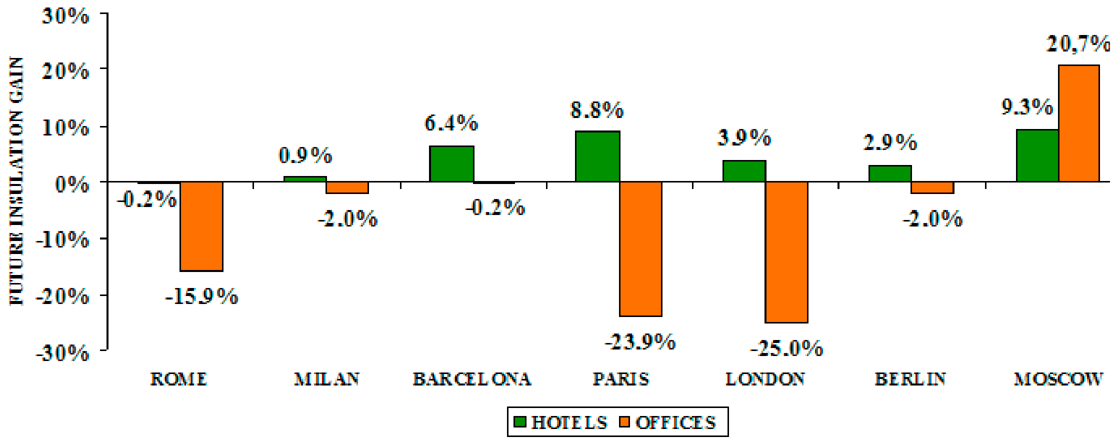

Fig. 6. Percentage gains due to the thermal insulation increase.

It is possible to deduce that:

- In office buildings, the insulation increase is often harmful for energy consumption, with the exception of Moscow, due to the higher endogenous loads caused by the higher level of insulation.
- In hotels, the insulation increase is energetically harmful in Milan and Rome, while it is advantageous in the other locations. It could be argued that there is a difference in behaviour between North and South Europe: Barcelona is an exception, because of the poor insulation level required by Spanish law. In any case, the gains for the increased insulation are always limited. In hotel buildings, the energy required for the domestic hot water production is extremely high and the thermal insulation does not affect this consumption.
- The consumption for cooling is much greater than the one for heating, even in Law level insulated buildings. In almost all cities, a Future insulation level clears the needs of heating inside the building: the only request is for fresh air treatment.

5. Conclusions

The path toward NZEB targets in buildings is not simple since it requires a conscious design based on the "whole building approach". In order to minimize buildings' energy consumptions, it is fundamental to find the most appropriate matching between envelope features and HVAC system configurations, in function of the different climatic conditions. Taking inspiration from Michelangelo Buonarroti, who said that "perfection is made by details", it can be said that the energy savings can be achieved only taking into account all the single details, even those that can appear more insignificant.

The paper shows that there is a virtuous path to be followed step-by-step. Each building is different with respect to the others, but there are some common solutions that can be followed everywhere.

Moreover, often the increase of the building thermal insulation is not the only way to reach NZEB ambitious targets. In some cases, indeed, it may results in higher power consumptions rather than in a reduction of consumptions (and costs), as it happens in the case of office buildings.

As a result, to achieve better energy performances, it is fundamental to work on the technical systems' side, for instance by varying the water flow in the hydraulic circuits, by reducing the primary air flow according to the actual presence of people or by reducing the electricity consumption of auxiliaries, as pumps and fans. The use of Polyvalent Heat Pumps is another possible way for reducing the overall energy consumption of buildings.

References

[1] International Energy Agency (IEA), Transition to Sustainable Buildings, Strategies and Opportunities to 2050, 2013.

[2] European Commission, A Roadmap for moving to a competitive low carbon economy in 2050, COM (2011) 112, Brussels: Belgium, 2011.

[3] Economidou M, Energy performance requirements for buildings in Europe, REHVA Journal, 2012.

[4] Corgnati SP, Fabrizio E, Filippi M, Monetti V, Reference buildings for cost optimal analysis: method of definition and application, *Appl Energ*, 2013, 102, 983-993.

[5] Energy.gov, Office of Energy Efficiency & Renewable Energy, 2017. Available at: http://energy.gov/eere/buildings/commercial-reference-buildings, Last access: January 2017.

[6] TABULA Webtool, 2017. Available at: http://webtool.building-typology.eu/#bm, Last access: January 2017.

[7] EN 15232:2012, Energy performance of buildings – Impact of Building Automation, Controls and Building Management, Brussels: European Committee for Standardization, 2012.

[8] UNI 10339:1995, Impianti aeraulici ai fini di benessere. Generalità, classificazione e requisiti. Regole per la richiesta d'offerta, l'offerta, l'ordine e la fornitura, Milan: Italian Unification Body, 1995.

[9] EN 15251:2007, Indoor environmental parameters for assessment of energy performance of buildings, addressing indoor air quality, thermal environment, lighting and acoustics, Brussels: European Committee for Standardization, 2007.

[10] ISO 18523-1:2016, Energy performance pf buildngs – Schedule and condition of building, zone and space usage for energy calculation – Part 1: Non-residential buildings, Brussels: International Organization for Standardization, 2016.

[11] UNI TS 11300-1: 2014, Prestazioni energetiche degli edifici - Parte 1: Determinazione del fabbisogno di energia termica dell'edificio per la climatizzazione estiva ed invernale, Milan: Italian Unification Body, 2014.

[12] Vio M, I costi invisibili dovuti alla errata regolazione degli impianti, Aicarr Journal, 2015, 31.

[13] Corgnati SP, Becchio C, Vio M, Prendin L, Magagnini M, Influenze delle scelte progettuali sui consumi globali dell'edificio, proceedings of Aicarr conference, Padova, 2016.

[14] Corgnati SP, Becchio C, Vio M, Babuin M, Ranieri M, Confronto tra impianti a tutt'aria VAV e ad aria primaria: l'importanza del consumo degli ausiliari, proceedings of Aicarr conference, Bologna, 2016.

[15] Vio M, Il recupero energetico dall'aria espulsa, Aicarr website, chapter 2.9, 2014.

[16] Vio M, Germano L, Babuin M, HVAC systems with variable primary flow: analysis on energy potential saving, proceedings of Aicarr Conference, Matera, 2017.

[17] Becchio C, Corgnati SP, Vio M, Prendin L, Magagnini M, Crespi G, HVAC solutions for energy retrofitted hotel in Mediterranean area, proceedingsta of Climamed conference, Matera, 2017.