Energy-environmental and cost assessment of a set of strategies for retrofitting a public building toward nearly zero-energy building target

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The purpose of this study was to assess an energy retrofit of a building representative of those in public tertiary stock, to improve energy performance toward nearly Zero-Energy Building (nZEB) requirements. The building is located in the campus of the Politecnico di Milano University (Italy). Several hypothetical improvements regarding the building envelope and plants were assessed in terms of energy savings, costs, and the reduction of greenhouse gas emissions. The results of the study show that it is possible to reduce primary energy demand and associated emissions up to 40% from the current values by adopting market-available and well-proven technological solutions for retrofit. Moreover, exploiting on-site renewable energy sources, the net energy consumption can be near zero. However, an economic analysis of the application of these technologies has highlighted many critical elements related to the implementation of some solutions. This is particularly true for actions related to the thermal insulation of the building envelope and to the installation of ventilation system with heat recovery. Since nZEB requirements are related to the concept of economic performance, this paper gives useful hints to better understand the viability of many commonly adopted actions and strategies for reaching such targets in building retrofit cases.

Keywords:
Nearly Zero-Energy Building
Retrofit strategies
Energy savings
Case study

1. Introduction

Existing buildings account for 40% of total energy consump-tion in the European Union. Therefore, their retrofit and the use of energy from renewable sources are fundamental to reducing the EU's fossil fuel consumption and greenhouse gas emissions.

European legislation has set out a cross-sectional regulatory framework of ambitious targets for achieving high performances in buildings. Key parts of this framework are the Energy Performance of Buildings Directive (EPBD) 2002/91/EC and its recast (Annunziata, Frey, & Rizzi, 2013). On May 2010, Directive 2010/31/UE (Directive, 2010), a recast of the EPBD, was adopted by the European Parliament and the Council of the European Union to strengthen energy performance requirements and to clarify and streamline some of the provisions from the 2002 Directive. Directive 2010/31/UE requires that each Member State sets minimum requirements for the energy performance of buildings and their elements with a view to achieving the cost-optimal balance between the investments involved and the energy costs saved throughout the lifecycle of the building. National minimum energy performance requirements should not be more than 15% lower than the outcome of the cost-optimal results of the calculation taken as the national benchmark.

In accordance with Directive 2010/31/UE (Directive, 2010), a nearly Zero-Energy Building (nZEB) is a building with a very high energy performance that requires nearly zero or very low amounts of energy. This energy demand should be mainly covered by energy from renewable sources, including energy from renewable sources produced on-site or nearby. The directive recommends that both new buildings and existing buildings, in case of major renovation, should achieve minimal energy requirements.

Many studies have investigated the economic and environmental aspects of the buildings. For instance, Kurnitski et al. (2011) studied cost-optimal solutions and nZEB energy performance levels by following the REHVA energy calculation methodology and the net present value method. Model calculations were conducted for an Estonian detached house to analyze the difference between

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the cost-optimal and nZEB energy performance levels. The authors concluded that a nearly zero-energy performance level is not yet cost optimal with current prices. They found the distance from a cost-optimal to nearly zero-energy performance level to be about 20%.

Other examples include Hamdy, Hasan, and Siren (2013) and Pikas, Thalfeldt, and Kurnitski (2014). Hamdy et al. (2013) introduced a multi-stage simulation-based optimization method to find cost-optimal and nZEB solutions in line with Directive 2010/31/UE (Directive, 2010). This method was applied for a case study of a single-family house in Finland. The authors explored different options for building envelope parameters, heat-recovery units, and heating/cooling systems, as well as various sizes of thermal and photovoltaic solar systems. Their results show that the optimal solution depends significantly on the selected heating/cooling system and the escalation rate of the energy price. Pikas et al. (2014) considered possible building fenestration design solutions, which account for both energy efficiency and cost optimality. They analyzed some alternative measures to achieve the nZEB level and their results show that existing nZEB solutions are not cost optimal, but this should change in the near future.

The new EU directives were taken into account in several building studies. Many of these studies are mainly focused on achieving energy efficiency solutions rather than on cost efficiency (Pikas et al., 2014). Some examples are Chidiac, Catania, Morofsky, and Foo (2011), Poirazis, Blomsterberg, and Wall (2008), Susorova, Tabibzadeh, Rahman, Clack, and Elnimeiri (2013), Kanagaraj and Mahalingam (2011), and Kneifel (2010). Specifically, Chidiac et al. (2011) developed a methodology based on non-linear regression analyses to screen office buildings for their current level of energy consumption and potential for retrofit application.

Other research studies have focused on lifecycle costs of the building (Hasan, Vuolle, & Siren, 2008; Kneifel, 2010; Marszal & Heiselberg, 2011; Pylsy & Kalema, 2008). For instance, Marszal and Heiselberg (2011) adopted the lifecycle cost analysis to a multi-family nZEB in Denmark, addressing three levels of energy demand and three alternatives of energy supply systems. They found that, to build a cost-effective nZEB, the energy use should be reduced to a minimum, leaving a small amount of leftover energy use to be cov-ered by renewable energy generation. Another relevant example is Hasan et al. (2008), who implemented a combined simulation and optimization approach to minimize the lifecycle cost of a single-family detached house in Finland. The combined approach enabled them to find optimized values of selected design variables in the building construction and HVAC system.

In Italy, Directive 2010/31/UE (Directive, 2010) was implemented by Law No. 90/2013 (LEGGE, 2013), which adopts a national methodology for calculating the energy performance of buildings, taking into account, among other things: the thermal characteris-tics of the building, its heating/cooling systems, light equipment, and hot water production plant. According to the same law, new buildings owned and occupied by public authorities in Italy must fulfill nZEB requirements starting from 2019, while all new build-ings must be nZEB from 2021. Moreover, based on the recent National Ministerial Decrees (D.M. 26/06/2015) (MiSe, 2015), the nZEB requirement has also been extended to existing buildings undergoing major renovation.

In particular, Lombardy was the first Italian region to transpose the D.M. 26/06/2015 (MiSe, 2015) into its own legislation (Regional Deliberation No. X/3868/2015) (DGR, 2015). This act is more strin-gent than D.M. 26/06/2015 (MiSe, 2015), as it states that all new buildings and existing ones undergoing major renovation in Lom-bardy must be nZEB starting from 2016.

The same D.M. 26/06/2015 (MiSe, 2015) foresees a national study, to be carried out by ENEA (Italian Agency for New Technologies, Energy, and Environment) and CTI (Italian Thermo-Technical Committee, supporting many laws and regulations in the thermo-energy field), to verify and monitor the evolution of the optimal energy performance requirements. Results will be used to tune and update future standards.

Fig. 1. Aerial photograph of the south facade of the building in the Città Studi campus.

From a collaboration agreement between ENEA and the Politecnico of Milano university,[1] the present paper explores the retrofitting of an existing building towards the target of upgrading it to nZEB status. An analysis of energy and environmental performance connected to a supposed set of retrofit measures together with a cost/benefit assessment of these measures constitutes the core of the study.

Although the present study refers to work concluded before the implementation of Law No. 90/2013 (LEGGE, 2013), it can contribute to a better understanding of some of the issues that arise when building retrofitting measures are implemented and energy analyses are coupled with economic features, to assess how these actions are effective for reaching the “status” of nZEB as stated by Italian law.

2. Case study description

The building chosen for this case study is a tower office built in the sixties and located in the Città Studi campus of the Politecnico di Milano University (Italy). It is mainly used as an office building for a university department and should undergo extraordinary maintenance mainly due to the extreme degradation of stoneware tiles. As shown in Fig. 1, the building presents a vertical unconditioned core where the elevators and staircases are located, a basement level, six floors for offices above the ground floor, and a recessed top floor used as the guardian’s home, equipped with autonomous air conditioning systems but decommissioned long ago then used as storage.

Therefore, the energy consumption of the guardian’s house was not included in this study. This also allows using the results of this work as a reference for future studies on office buildings.

The basement is used as a press centre and consists of a conditioned open space with a semi-double-height. One wall of the basement is built directly in contact with ground for about 2/3 of its length.

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[1] In the frame of the MSE (Italian Ministry of Economic Development)-ENEA Research Program: “*Ricerca di sistema elettrico*”. http://www.enea.it/it/Ricerca_sviluppo/ricerca-sistema-elettrico.

Table 1
Main building information.

Building element	Total envelope area	Building volume	Shape factor
	3213 m^2	12952 m^3	0.25 m^3
Envelope	*Envelope surface* [m^2]	*Window surface* [m^2]	*Opaque surfaces* [m^2]
Slab on ground	510	–	510
Underground walls	80	–	80
North facade	456	121	335
South facade	468	155	313
East facade	655	216	439
West facade	534	134	400
Roof	510	–	510

Table 2
Physical and thermal characteristics of the building elements.

Building element	*U*-value [W/(m^2 K)]	Mass per frontal area [kg/m^2]	Specific heat per frontal area [kJ/(m^2 K)]
External walls	1.34	270	233
Basement walls	2.30	606	532
Roof	1.54	436	371
Slab floors	0.88	434	366
Intermediate floors	1.39	470	400
Internal partition walls	1.60	106	100
Windows	5.13	–	–

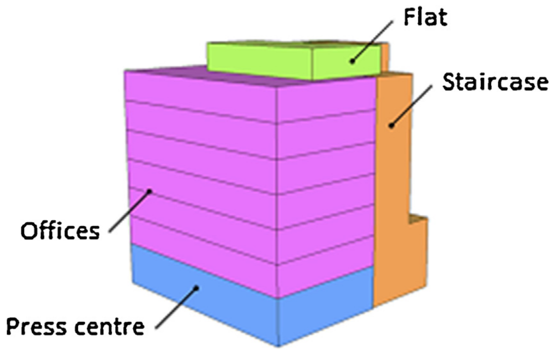

Fig. 2. Three-dimensional pattern of the simulation model and zone uses.

Table 1 reports the main characteristics of the building. This building has very similar properties to the "tower block building" – one of four "building archetypes" representative of Milan building stock according to the study of Caputo, Costa, and Ferrari (2013) – which has a shape factor of 0.26, the same external uninsulated walls construction made by hollow bricks, single glazed windows, and an HVAC system having fan coils as room terminals.

Buildings on the campus are not equipped with individual energy meters, so individual bills are not available. The evaluation of the energy performance was conducted using the TRNSYS tool (Klein et al., 2004), which also includes typical meteorological data for Milan. Fig. 2 shows a 3D sketch of the building that considers the main uses of the spaces as well as construction and system characteristics.

2.1. *Electric loads, occupation, and ventilation*

The internal loads and time schedules of occupation have been analyzed. Occupant density was set according to the standard UNI 10339 (UNI, 1995), which defines a rate of 0.06 persons per m^2 in the offices, corresponding to 19 people per level. This value matches what can be really observed in the building (e.g. the occupation density value of the press centre is related to presence of the staff and the users, too). The electric load for artificial lighting and office appliances was assumed to be equal to 15 W/m^2 (in the press centre, the lower number of installed light bulbs and of electric appliances is offset by copy machines and plotters), according to the standard UNI TS 11300-1 (UNI, 2008a). This data underestimates the actual power surveyed in the case study areas, but it complies with the real peak power, which obviously does not coincide with the installed power.

Occupation, lighting, and appliance-use profiles were created by assigning three levels of intensity to every workday (100%, 70%, and 40%), within a working time from 9:00 to 20:00. An electric load density of 2 W/m^2 was set for the electric appliances on stand-by mode and for the security lighting set during off-work hours. The building is naturally ventilated, but, in the model, in order to further evaluate the effect of a mechanical ventilation system, the fresh air flow rate was assumed to be in accordance with the standard UNI 10339 (UNI, 1995), which sets a value of 11 m^3/(s person). As a result, the maximum volume flow rate is 750 m^3/h in each level, and it is modulated according to the occupancy schedules. The air infiltration rate through the envelope was set to 0.20 air changes/h.

The unconditioned spaces were also modeled as buffer spaces close to the air-conditioned areas. For the vertical unconditioned core, a lighting power density of 8 W/m^2 and a time activity from 8:00 to 20:00 were fixed according to the Italian standard UNI TS 11300-1 (UNI, 2008a). The lighting load was changed to 1 W/m^2 during the night. The air change rate was set equal to the air infiltration rate, i.e. 0.20 air changes/h. This is the only data used for modeling the guardian's home.

2.2. *Characteristics of building construction*

Construction characteristics were gathered by the analysis of archive data and by direct observation. The physical and thermal properties of the building elements are shown in Table 2.

The windows of the building have single glazing, an aluminum frame without a thermal break, and venetian blinds. Manual activation of the shading elements was simulated by fixing a Shading Factor of 30% for values of direct solar radiation incident on the glass surface above 100 W/m^2.

2.3. *Heating and cooling plants and systems*

In order to simulate the performance of heating and cooling plants and systems, the efficiencies of each subsystem (generators,

Table 3
Emission, regulation, and distribution efficiencies of H/C plants and systems.

Phase	Winter efficiency	Summer efficiency
Emission	0.940	0.980
Regulation	0.940	0.940
Distribution	0.955	0.990

distribution, emission, and control) and auxiliary electric consumption were assessed according to technical standards UNI TS 11300-2 (UNI, 2008b) and UNI TS 11300-3 (UNI, 2010).

Each office is heated and cooled by a two-pipe fan coil, with individual thermostat, for a total of 15 units per floor. The airflow rate of each fan coil ranges from 200 to 400 m^3/h, with an average electric power absorbed for ventilation of 50 W.

The adopted emission, control, and distribution efficiencies' val-ues in winter and summer are shown in Table 3.

The building is connected to a district heating network and the overall efficiency of the heating systems was assumed equal to 0.80. Cooling is supplied via an air-to-water chiller installed a few years before the study. A load factor-efficiency curve was built according to the technical data sheet of the chiller and the UNI TS 11300-3 standard, and was included in the simulation model in order to use proper energy efficiency ratio (EER) hourly values consistent to load time series. The standard heating period for Milan is from October 15 to April 15; for the rest of the year, the demand has been simulated assuming a cooling set point of 26 °C, always active during the work hours.

3. Retrofit strategies

Aiming to plan an effective retrofit for the building, some widespread and proven technologies were chosen:

- improvement of the thermal insulation envelope, by implementing a conventional refurbishment of the facade;
- replacement and upgrading of heating and cooling plants and the HVAC system;
- renovation and installation of advanced controls of lighting systems; and
- installation of a photovoltaic plant.

3.1. Building envelope

Actions voted to reduce thermal losses through the building envelope have been designed to be compliant with existing "minimum requirements" for the energy performance of the buildings in Milan (by regional decree DGR, 2008). In general, the building envelope is supposed to be improved by adding polystyrene panels on walls and on the roof, and by replacing the windows. The polystyrene panels displaced on vertical opaque walls would be overlaid with new stoneware tiles to completely replace the existing, degraded covering. On the roof, a thermal insulation layer would be placed over the slab below the existing sloped metal sheet. All existing windows would be replaced with new ones having a thermally broken aluminum frame and double-pane glass.

A sensitivity analysis on target thermal insulation values was conducted by varying the thickness of the polystyrene panels and the glazing technologies of the windows.[2] Three cases were examined:

- 10 cm-thick panels and double-glazed, low-emissivity windows, as related to the thermal insulation requirements by law (DGR);
- 15 cm-thick panels and double-glazed, argon-filled low-emissivity windows, which lead to an additional 30% decrease in U value by law (DGR-30); and
- 20 cm-thick panels and triple-glazed, krypton-filled low-emissivity windows, which lead to an additional 50% decrease in U value by law (DGR-50).

3.2. Building equipment

Actions on building equipment include the following improvements:

3.2.1. Artificial lighting (SENS)

To reduce electricity consumption for artificial light and improve visual comfort, this specific action deals with the installation of combined occupation sensors and daylight sensors. Each space will be equipped with dimmed lighting systems to meet specific luminous levels according to several visual tasks. This action conservatively leads to a 45% decrease in lighting load and consumption (Ferrari & Bonomi, 2008), thanks to the more efficient use of the luminaires.

3.2.2. Heating and cooling (GEOT)

3.2.2.1. Replacement of existing heating and cooling plants. The existing layout, based on a heat exchanger connected to the district heating network of the campus and a centralized air-water chiller for cooling, will be substituted by a groundwater heat pump system that will be used for all tasks. A heat/cold sink is the aquifer settled 30 m below ground level. Heat transfer will be achieved by abstraction of water from a vertical open loop made of two wells. The system will have both a coefficient of performance (COP) and an energy efficiency ratio (EER) of 5.1, which are the minimum nominal values required by the Legislative Decree No. 28/2011 (Italian Parliament, 2011) (National implementation of the Directive 2009/28/EC). Hourly values have been calculated according to operating temperatures and by means of load factor-based efficiency curves according to the standard UNI TS 11300-3 (UNI, 2010).

3.2.3. Ventilation (MVS)

3.2.3.1. Installation of a mechanical ventilation system (MVS) with heat recovery. While a single centralized plant would be too invasive and costly, the better solution is to install an MVS on each floor. According to technical sheets of products available on the market, the specific fan power (SFP) was set to 0.19 $W/(m^3\ h)$ and the heat recovery efficiency equal to 0.85, which is a conservative value con-sidering the typical certified figures up to 0.92. In order to calculate the air head losses, the airflow distribution was assumed to be real-ized using circular pipes with a diameter of 250 mm, which ensures a maximum air velocity of 5 m/s. The total length of the air distri-bution system was set to 55 m on each floor. Fans require in total an electric power of 0.14 kW, 0.11 kW, or 0.06 kW for airflows of 750 m^3/h (100% of occupancy), 563 m^3/h (70% of presence), and 300 m^3/h (40% of presence), respectively. The MVS was simulated to passively cool the spaces in the summer nights (from 23:00 to 7:00, according to UNI TS 11300-1 (UNI, 2008a)). In this operation mode, a proper bypass valve kept the heat recovery process from affecting the ventilation flow, which was assumed to be constantly equal to the maximum airflow, i.e. 750 m^3/h on each floor. A more detailed analysis demonstrated that the reduction of the energy consumption due to the passive night cooling is higher than the energy consumptions of the MVS.

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[2] "...defining measures aimed at increasing the number of buildings in line with minimum standards in force or better overcoming the energy performance required is necessary", from 2010/31/EU Directive.

Table 4
PV energy performance.

	Roof	Facade			Total
		South	East	West	
Surface [m^2]	300	92	134	144	670
Nominal power [kW$_p$]	44.5	13.7	25.5	21.7	99.8
Annual energy supply [MWh]	46.2	10.5	12.9	14.0	83.5

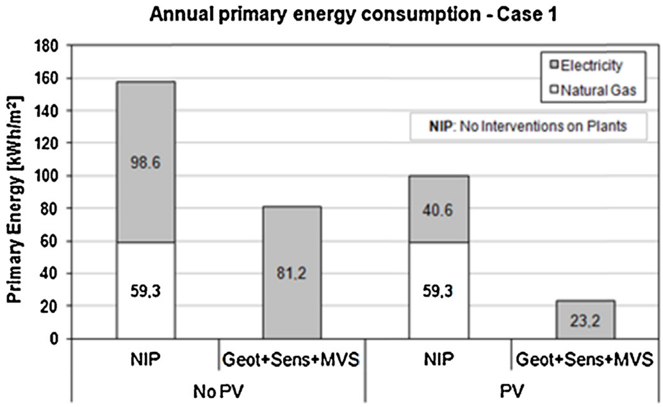

Fig. 3. Case 1: annual primary energy consumption.

3.3. *Photovoltaic (PV) plant*

Because the building has good solar exposure, the installation of a photovoltaic (PV) plant with panels placed on the roof as well as south, west, and east facades, is presumed to be effective. The PV plant was assumed to be made of mono-crystalline silicon panels with a nominal efficiency of 15% (±4%/K) and to be grid-connected.

The total PV surface area of the roof is 300 m^2. This value was set according to the gross surface of the roof (510 m^2) and takes into account the aim of avoiding mutual shading of the arrays.

The panels to be installed on the vertical walls have a total surface area of 370 m^2. These panels act as string-courses on walls with windows while totally covering the western opaque facade.

The annual electric energy produced by the photovoltaic panels was calculated by using the RETSCREEN simulation tool.[3] Results are shown in Table 4.

4. Primary energy and greenhouse gas (GHG) balance

The energy and environmental effects of the retrofit measures were analyzed for creating a matrix of cases, adopting the primary energy conversion factors suggested by UNI TS 11300-2 (UNI, 2008b) (1 for natural gas, 0.45 for electricity) and, concerning the emission factors, according to the Lombardy Regional Decree n. 5796/2009 (0.1998 kg CO_{2eq}/kWh for natural gas and 0.4332 kg CO_{2eq}/kWh for electricity).

The main results are grouped and represented in the following sections according to two main reference cases related to the building envelope:

- Case 1. Building envelope at the original state (BCS).
- Case 2. Building envelope improved consistently with the thermal insulation requirements by law (DGR).

Actions related to plants and systems were added to these two cases. The results of the investigation are shown in Figs. 3–6.

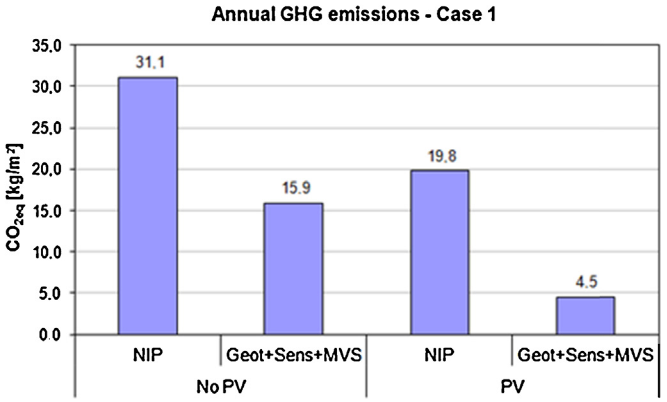

Fig. 4. Case 1: annual GHG emissions.

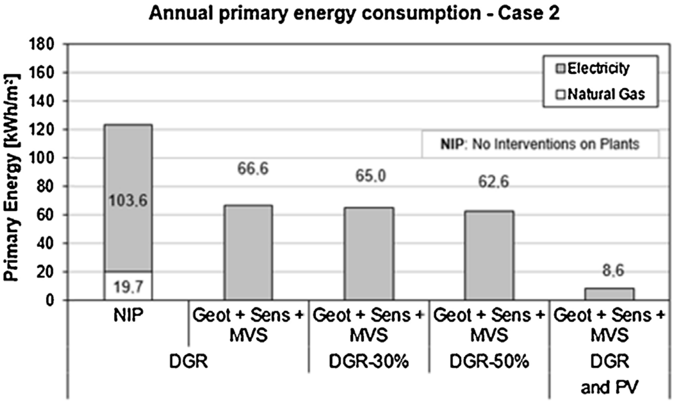

Fig. 5. Case 2: annual primary energy consumption.

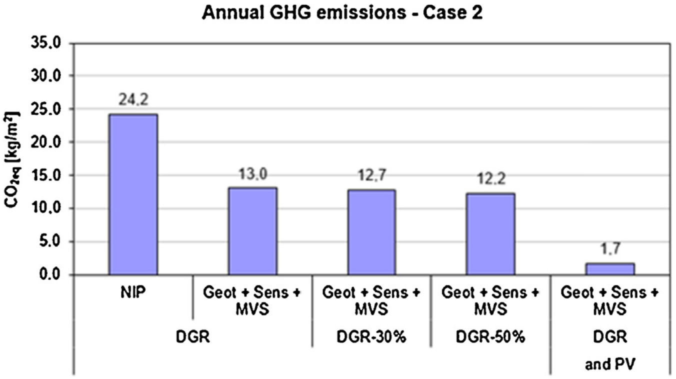

Fig. 6. Case 2: annual GHG emissions.

In Case 1 (Figs. 3 and 4), the implementation of the main system and plant retrofit measures would reduce the annual primary energy consumption by 50%. A further dramatic reduction (from 81 to 23 kWh/m^2) is achievable when the PV contribution is also con-sidered in the energy balance. This last option would reduce the GHG emissions from the original figure of 31.1–4.5 kg/m^2.

By comparing the charts of Case 1 with those of Case 2 (Figs. 5 and 6), it can be noted that when the building envelope is supposed to be insulated according to “DGR” requirements the annual primary energy consumption is reduced by 20%, without implementing any improvement in systems and equipment, while upgrading to “DGR-30” and “DGR-50” thermal insulation levels would lead to a further reduction of only 2% and 6%, respectively. The minimum energy consumption (8.6 kWh/m^2) is achievable when the PV system is considered in Case 2 together with the intro-

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[3] RETScreen International, Natural Resources Canada, www.retscreen.net.

Table 5
Costs related to the conventional replacement of the stoneware cladding.

Item	Quantity	Cost [k€]
Removal of the stoneware cladding	1487 m^2	37.18
Collection and transport of waste to landfill	ca. 100 m^3	8.50
Cleaning by high-pressure water jet machine	1487 m^2	10.41
Rustic plaster with cement and sandstone (supply and installation)	1487 m^2	32.72
Stoneware cladding (supply and installation)	1487 m^2	126.76
Rental of scaffolding	2113 m^2	46.49
Site works (supply of plastic sheets and anti-theft included)	–	8.00
Total		270.08

duction of a geothermal heat pump, advanced controls of lighting system, and installation of a mechanical ventilation system with heat recovery. This also would reduce the GHG emission down to 1.7 kg/m^2.

5. Costs of intervention

5.1. Envelope

Each scenario has also been assessed from an economic perspective. Tables 5 and 6 show the costs related to the replacement of the stoneware cladding and to the improvement of the building's thermal insulation, respectively.

5.2. Building equipment and PV plant

The cost of the groundwater heat pump (200 kW-sized) was assumed to be 65,000 €, including accessory devices and the removal of the existing chiller. Maintenance costs have been presumed to be equal to the ones of the existing chiller (no additional costs have been considered). Moreover, since the existing chiller was recently installed, it was supposed to be reused in other buildings of the campus. For this reason, disposal costs were ignored. The total cost of the groundwater system also includes the cost of the vertical open-loop system, having considered the groundwater level of the site. This cost was calculated to be 12,000

The considered presence/daylight sensors kit to be installed in each space was selected from the market among the ones that can easily upgrade the existing equipment. A substitution rate of 5% per year over a period of 30 years was assumed in order to calculate the annual maintenance cost of these devices. More details are shown in Table 7.

The MVS consists of seven units with heat recovery evenly distributed in each floor. For units installed in office spaces, air extraction is made through a plenum confined by a false ceiling in the corridors.

The maintenance program includes a cleaning of all units (two times per year) and the replacement of the filters (at the beginning of the winter season).

Table 7
Cost of the occupation/daylight sensors and controllers.

	Office spaces	Press center	Total
Quantity of sensors	1 sensor/office 15 offices/floor × 6 floors	60 lamps 1 sensor/15 lamps	
	90 sensors	4 sensors	94 sensors
Cost of sensors	Material	Installation	
	110 €/each	100 €/each	210 €/each
Installation cost			19,740 €
Maintenance cost			517 €/year

Table 8
Cost of the mechanical ventilation system.

	Unit cost	Quantity	Total
Ventilation unit	8000 €/each	7 (1 unit/floor)	56,000 €
Ducts and nozzles	5000 €/office storey	6 office storeys	32,500 €
	2500 €/press centre	1 press centre	
Ceiling plenum	40 €/m^2	60 m^2/floor × 6 floors	14,400€
Installation cost			102,900 €
Maintenance cost			1400 €/year

The unit cost of the PV plant was assumed to be 1800 €/kW including design and installation, which leads to a total cost of 186 k€. The maintenance cost was assumed equal to 2%, including the inverter replacement every ten years. Table 8

6. Energy-economic analysis

The building retrofit measures were analyzed not only with respect to their efficacy in terms of primary energy consumption but also according to their economic performances.

The economic evaluations have been conducted referring to the total annual cost, the Net Present Value and the Payback Time. Sensitivity analyses where performed to catch the impact of variations of important parameters such as discount and cost of energy.

The annual cost, defined as the sum of the annual cost of building management and maintenance and the annual discounted installment of initial costs, is given by the product of the cost of the initial investment and the annual discount factor.

Concerning the annual discount factor, which distributes the investment of initial capital in annual constant installments, the calculation period of 30 years and the interest rate of 3% of the baseline scenario as provided by the (European Parliament, 2012) have been considered.

The calculation does not include incentives, tax deductions, etc. Electricity and natural gas costs were set to 0.08 €/kWh and to 0.18 €/kWh respectively. Results are shown in Figs. 7–9.

Fig. 7 shows the energy/economic performance (EEP) of the retrofit solutions applied to the building at its current state (BCS). As a result, the retrofit measures and the PV installation would improve both the energy and the economic performance of the

Table 6
Additional costs related to the improvement of the building's thermal insulation.

Item	Quantity	Cost [k€]		
		DGR	DGR-30	DGR-50
Removal of windows	626 m^2	18.77	18.77	18.77
Collection and transport of waste to landfill	ca. 60 m^3	8.50	8.50	8.50
Windows (supply and installation)	626 m^2	500.60	531.88	563.17
Insulation of external walls (supply and installation)	1487 m^2	104.11	118.98	133.85
Insulation of roof (supply and installation)	310 m^2	7.44	9.92	12.40
Removal and repositioning of the roofing sheet	310 m^2	12.40	12.40	12.40
Rental of scaffolding (additional period)	2113 m^2	8.45	8.45	8.45
Total		660.27	708.91	757.55

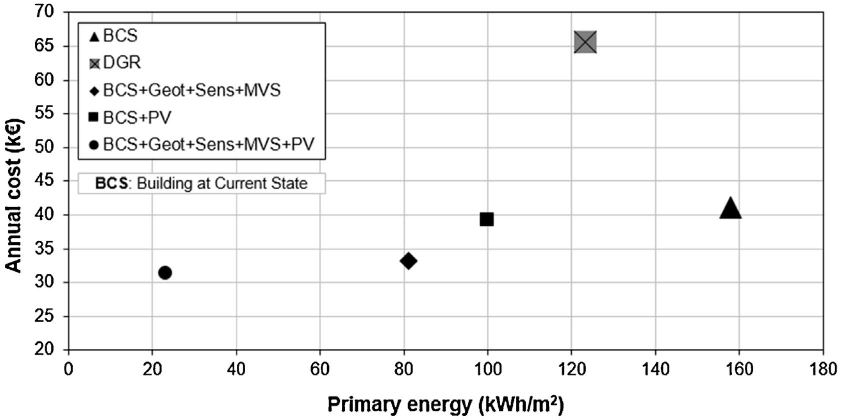

Fig. 7. EEP of retrofit solutions on the building at current state—Case 1.

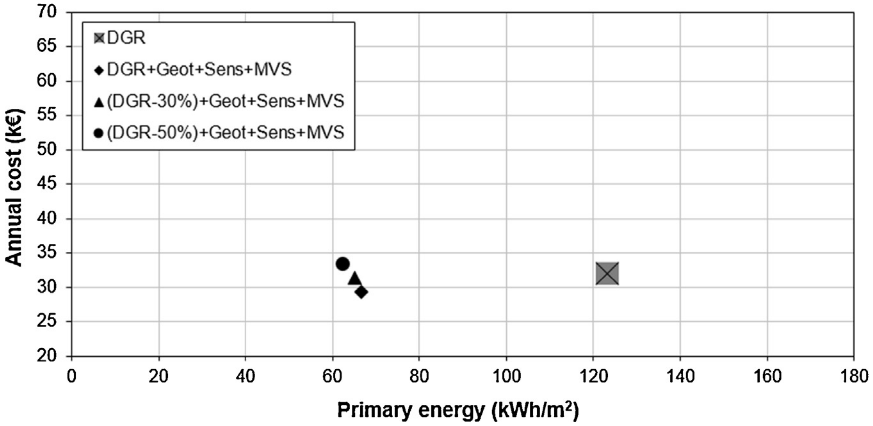

Fig. 8. EEP of new building equipment based on building envelope upgraded to Case 2 (DGR) and coupled with increased level of thermal insulation.

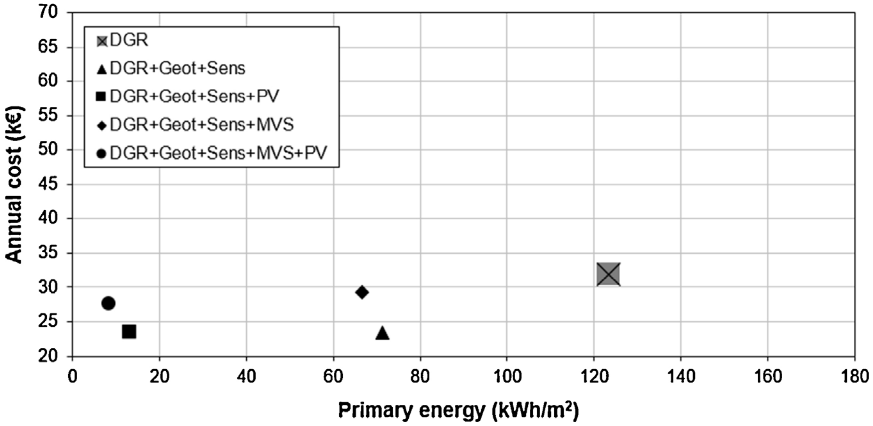

Fig. 9. EEP of new building equipment solutions on the Case 2 (DGR) building envelope.

building, giving a better performance when implemented together. On the other hand, the thermal insulation of the envelope based on the laws in force would improve only the building energy performance. This result is mainly affected by the high cost of window replacement, which is about 80% of the total cost required for improving the thermal insulation of the entire building.

Assuming the necessity of insulating the building envelope to comply with the standard in force (ref. DGR), the new building equipment reveal their effectiveness, as reported in Fig. 8.

The same figure shows that, from an economic perspective, increasing the thermal insulation level beyond the standard is not convenient. Due to an increase in the total annual cost, the economic performance degrades when the thermal insulation envelope varies from the level compliant to “DGR” to the more restrictive “DGR-50”.

Based on the same DGR reference case, Fig. 9 shows that, among the overall plant/system retrofit solutions, the MVS measure is not cost-effective. In fact, the cost of installation of a new ventilation system, including air ducts and fans, would affect the overall economic performance. This result could be overturned if the building would have been originally equipped with an all-air-conditioning

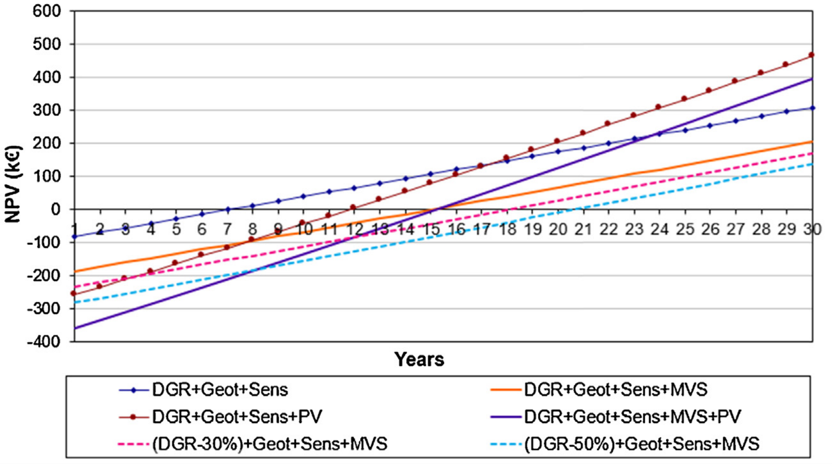

Fig. 10. NPV and Pay-Back Times for different interventions for the Case 2 (DGR) building envelope.

Table 9
Results of the sensitivity analysis.

Sensitivity parameters	Sym.	Ref.	Scenarios						
Energy cost increase rate	a	**3%**	**3%**	**3%**	10%	5%	**3%**	10%	5%
Discount rate	r	**3%**	5%	10%	**3%**	**3%**	**3%**	5%	10%
	Pay-back time [years]								
DGR + Geot + Sens		7	7	10	5	7	7	6	9
DGR + Geot + Sens + PV		12	13	25	8	11	12	9	17
DGR + Geot + Sens + MVS		15	18	»30	10	13	15	11	26
DGR + Geot + Sens + MVS + PV		15	18	»30	10	13	15	11	26
(DGR-30%) + Geot + Sens + MVS		18	22	»30	11	15	18	13	39
(DGR-50%) + Geot + Sens + MVS		21	27	»30	12	17	21	14	»30
	PBT	Percent PBT variation							
DGR + Geot + Sens		7	0.0%	42.9%	−28.6%	0.0%	0.0%	−14.3%	28.6%
DGR + Geot + Sens + PV		12	8.3%	108.3%	−33.3%	−8.3%	0.0%	−25.0%	41.7%
DGR + Geot + Sens + MVS		15	20.0%	»100%	−33.3%	−13.3%	0.0%	−26.7%	73.3%
DGR + Geot + Sens + MVS + PV		15	20.0%	»100%	−33.3%	−13.3%	0.0%	−26.7%	73.3%
(DGR-30%) + Geot + Sens + MVS		18	22.2%	»100%	−38.9%	−16.7%	0.0%	−27.8%	116.7%
(DGR-50%) + Geot + Sens + MVS		21	28.6%	»100%	−42.9%	−19.0%	0.0%	−33.3%	»100%

system, since the heat recovery unit would be the only device to be installed in order to obtain the same energy performance effect.

Moreover, adopting a variation trend in the cost of energy and of the inflation rate characterizing the previous five years (assumed as 3% and 1% respectively), the Net Present Values (NPV) of different interventions for reference Case 2 (DGR) have also been calculated, along with the Pay-Back Times (Fig. 10).

As shown in Fig. 10, the pay-back time (PBT) of the DGR reference case is 7 years when a geothermal heat pump and occupation and daylight sensors are supposed to be added to the system (DGR + Geot + Sens). On the other hand, when the building is supposed to be further improved by installing a photovoltaic plant (DGR + Geot + Sens + PV) or a mechanical ventilation system with heat recovery (DGR + Geot + Sens + MVS), the pay-back time goes up to 12 years and to 15 years, respectively.

A figure of 15 years is also obtained when both a photovoltaic plant and all the assumed building equipment improvements are supposed to be added to the system (DGR + Geot + Sens + MVS + PV). In this case, due to the installation of the photovoltaic system, the investment cost would be doubled but the cash flows would be higher than the “DGR + Geot + Sens + MVS” case.

Finally, when the building envelope is supposed to be “over-insulated” according to DGR-30 or DGR-50 requirements, the pay-back time is further increased, up to 18 years and to 21 years respectively.

A sensitivity analysis on the pay-back time has been also performed. The figures adopted for the sensitivity parameters and the results of the sensitivity analysis are summarized in Table 9.

From the results of the sensitivity analysis, it is possible to note that the increase of the cost of energy causes very significant reduction of PBT (up to 43% for an increase of 10% per year and 19% for an increase of 5%). This is true also in the case of contemporary increase of the discount rate (5%), where reductions of about 25% of PBT are associated to many investments. The relative impact of changes of the discount rate is very important on the investment return. The scenario with a discount rate of 5% gives increases from about 10% to 30%, while the one with the rate assumed equal to 10% makes all the investments unaffordable, as does the case of a certain increase (5% per year) of the cost of energy.

7. Conclusions

The aim of this work was to explore some representative retrofit options for an existing office building located in Milan with a target of achieving very high energy performance and primary energy demand close to zero.

The results demonstrated that retrofitting the building with proven and widespread technologies could dramatically reduce the primary energy consumption. This also would lead to a 40% reduction in greenhouse gas emissions. Good reduction can be achieved by increasing the thermal resistance of roofs and facades, while the adoption of targets over the usual standard levels would not lead to a proportional increase of performance.

The installation of a groundwater heat pump leads to very good results, although the current H/C is quite new and heat is distributed by a local network. A further reduction of the primary energy consumption could be achieved if a grid-connected PV system is installed on the roof and the facades of the building. More precisely, in the examined case study, primary energy consumption could be reduced down to 5% of the current rate.

The retrofit solutions (regarding plants/systems) that do not include improvements on the building envelope are generally the most cost-effective options. Installation of controlled mechanical ventilation systems with heat recovery is very effective from an energy point of view (primary energy consumption could be reduced down to 15%), but their extra costs would be not affordable under the economical point of view.

In any case, the economic performance of a retrofit solution can be strongly affected by parameters such as energy cost and discount rate. This clearly emerges from the results of the sensitivity analysis, performed in the energy-economic analysis of the study.

A better understanding of the economic issues related to retrofit strategies for existing structures is a key aspect in studies on nZEBs. In fact, although the definition of nZEB is strongly related to the cost effectiveness of technical solutions to be adopted, many of these show poor economic performance.

Main results of the present study could be extended to most of the buildings belonging to the same building archetype. However, as each building has its own peculiarities, the task of defining a set of actions correspondent to the "optimal cost" target is not easy. Any study related to country strategies would be based on a wide analysis of case studies on representative building archetypes and proven technologies.

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