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Comparative energy and economic performance analysis of an electrochromic window and automated external venetian blind

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Abstract

A virtual test cell representing a portion of an office building was modeled in order to evaluate the energy balance and the economic convenience related to the use, as solar control devices, of a switchable electrochromic glazing system (EG) and of an automated external venetian blind system (VB). Furthermore, results were compared with a so-called base case (BC) of the glazed component, with no exterior solar shading. The virtual test cell is supposed located in Milan, Italy. The operation of both shading systems was set in order to minimize undesirable solar heat gains during cooling season and to maximize them during heating season and also in order to optimize the daylighting performance without having glare effect on the work plane. The energy balance of the selected systems was done considering the annual primary energy consumption for heating, cooling, lighting, shading system operation and the glazed systems' embodied energy annual quota. Finally, a further comparison in terms of economic convenience was done. Simulations were performed using EnergyPlus 7.0 dynamic simulation engine in conjunction with BESTenergy Graphic User Interface.

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Keywords: electrochromic glazing (EG); venetian blind system (VB); shading optimization in heating, cooling and lighting

Nomenclature

BC	Base Case of the glazed component with no exterior solar control systems
VB	Venetian Blind shading system
EG	Electrochromic Glazing system

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1. Introduction

Nowadays, artificial lighting together with cooling represents the dominant energy use and peak electricity demand in office buildings. For this reason, window solar control is a very important aspect in order to improve energy performance in buildings, and national Governments begin to take care of this item. In facts, giving an example, Italian regulations oblige to provide, in all new buildings, adequate solar control systems [1]. Furthermore, the new European building energy performance regulation [2] made mandatory that, from December 2020, all new buildings must be nearly zero energy (nZEB) with very high energy performance. Therefore, dynamic window technologies coupled with daylighting controls designed to optimize daylight admission and solar heat gains rejection when needed, starts to become an important aspect to improve in Architectural designs [3]. By the way, these technologies needs also to be competitive from the economic point of view to have a large diffusion in building constructions.

For the above reasons, the present study was done, in which a virtual test cell (representing a portion of an office building in Milan) was modeled in order to compare the energy and economic balance of two different kinds of solar control devices: an Electrochromic Glazing system (EG) and an automated external Venetian Blind system (VB). Furthermore, results were compared with a so-called Base Case (BC) of the glazed component, with no exterior solar control systems.

The systems were set in order to minimize undesirable solar heat gains during cooling-time and to maximize them during heating-time, in conjunction with the optimization of daylighting performance and avoiding inside glare effect. The annual energy balance was based on primary energy consumption for cooling, heating, lighting and shading operation, included the systems' annual quota of embodied energy (EE). Then, economic convenience evaluation was based on the net present value of the three systems, considering both components' construction and energy consumption costs.

Dynamic energy simulations of the virtual test cell were done using EnergyPlus 7.0 calculation engine and BESTenergy, a graphic user interface developed by Politecnico di Milano.

2. Description of the test cell and boundary conditions

2.1. Test cell location and geometry

As explained above, the test cell was assumed to be a part of an office building in Milan. This location was chosen because requires to be very careful on both cooling and heating performance of the building. So, the corresponding Milan-Linate climatic file was used. Weather data came from Italian climatic data collection "Gianni de Giorgio" [4].

The test cell was described as a single thermal zone 8m (length) x 4m (wide) x 3m (high) with a single $4m^2$ window facing South direction (Fig.1(a)).

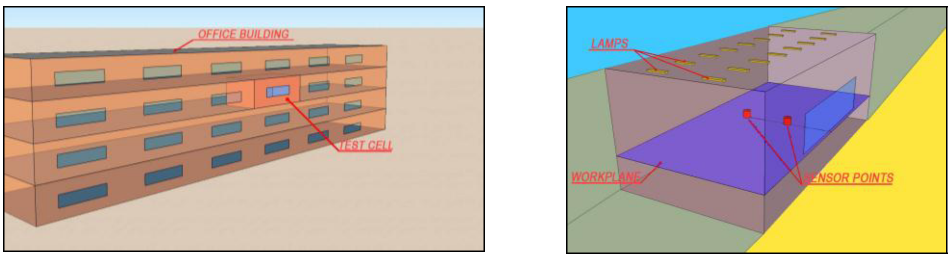

Fig. 1. (a)Perspective view of virtual Test cell modeled in BESTenergy as a part of an office building; (b) perspective view of the test cell showing the position of the sensor points.

2.2. Opaque envelope characterization

Only the southern wall was assumed to be an exterior surface, while floor, ceiling and the other walls were considered as adiabatic surfaces. Exterior wall construction was assumed as described in Table 1, because it already resulted a quite good solution in Milan climate both in cooling and heating energy performance [5].

Table 1. Exterior wall layer description and material thermal properties, starting from the outermost one

	Material description	Thickness (m)	Th.cond. (W/mK)	Density (kg/m^3)	Spec. heat (J/kgK)	Th.Resist. (m^{2}K/W)
1	Outer plaster	0.02	0.35	1200	1090	0.06
2	Polystyrene insulation	0.085	0.036	20	1340	2.36
3	Brick masonry	0.24	0.72	800	840	0.33
4	Inner plaster	0.02	0.35	1200	1090	0.06

2.3. Window and shading systems

The BC case has a low-emissive glass coupled with a clear float glass and an argon filled gap. The main optical and thermal properties are summarized in the first line of Table 2.

The BC window is not coupled with any exterior solar control system. Then, glazing system needs to have itself a behavior to partially block solar radiation to avoid overheating and local discomfort sensation. This is the reason why this kind of glazing, with a low solar heat gain coefficient, was chosen for BC system. Glare is avoided by a manually operated interior fabric shading.

The VB differs from the previous one firstly by its shading system which consists of an external aluminum venetian blind with horizontal slats. Slats are automatically lifted up and down or rotated depending on internal thermal and visible comfort. Because of solar control is ensured by venetian blinds, glazing system doesn't need to have a very low solar heat gain coefficient. Then, a generic double glazing with argon filled gap was chosen, which presents optical and thermal properties reported in the second line of Table 2. No interior shades are provided and glare control is ensured by exterior slats.

The EG system consists of an Electrochromic Glazing coupled with a clear float glass and an argon filled gap. No further shading systems are provided. EG optical properties vary from a total transparent state to a minimum 20% state of transparency. No darker condition of the EG was considered in order to avoid extra artificial lighting consumption. In the 3rd an 4th line of Table 2, main optical and thermal properties of both of the EG states [7] are described.

An aluminum thermal brake frame was used in each cases. It's important to highlight that in all cases the glazing U-values are very similar so the energy performance differences will be not caused by the components' thermal properties but only by solar radiation control skills.

Table 2. Main optical and thermal properties of analyzed cases' glazing [7]

	SHGC (-)	SC (-)	Visible transmit. (-)	U-value (W/m^{2}K)
BC glazing	0.462	0.531	0.621	1.436
VB glazing	0.759	0.872	0.754	1.636
EG (fully transparent state)	0.468	0.538	0.625	1.641
EG (20% visible transmittance)	0.163	0.188	0.213	1.641

2.4. Ventilation rates and internal conditions

Total internal gains rate was set, according to the local building regulations, equal to 20 W/m^2 during the occupation time (in week days from 7:00 am to 5:00 p.m.) and to 2 W/m^2 in the remaining period [8]. Light heat gains actually vary according to artificial lighting system operation. In order to separate the heat gains coming from the lights, a simulation of the BC was run to estimate an annual average of electric consumption due to lighting system. Finally a mean annual value of lighting heat gains equal to 5 W/m^2 was subtracted by the cumulative internal gain rate value.

The ventilation was assumed to be natural. The airflow rate was set to 1.58 air changes/hour during occupation time [9].

Set-point temperatures for heating and cooling system were set, respectively, to 20 °C and 26 °C [8].

2.5. Heating and cooling systems

Heating loads were assumed to be covered by a traditional gas boiler and fan-coil emitters with an efficiency of 89%. Cooling system consists of an air-to-air heat pump with a mean seasonal efficiency of 2.5 assumed for Milan climate conditions.

2.6. Lighting system

A lighting system with fluorescent recessed lamps was considered. The system was sized using the total flux method [10] in order to ensure an illuminance level of 500 lux on the work plane (0.9 m height above floor plan).

According to this method, luminaries are supposed to be uniformly distributed through the ceiling. In order to have an illuminance level of 500 lux on the work plane the test cell requires 48372 lm in condition of external total darkness. Furthermore, considering a luminous efficiency of the selected fluorescent lamps equal to 96 lm/W [10], the electric power absorbed by the lighting system in condition of external total darkness turned out to be 503 W. The lighting system was set to be switched on once the design illuminance level was not met by the natural light. Its power absorption will then be dimmed to meet the illuminance quota not covered by daylighting.

3. Energy performance evaluation

The energy needs including heating, cooling, lighting and shading device operation were evaluated for the three analyzed cases. Also, an annual quota of shading systems' embodied energy was added for a complete energy efficiency evaluation. To compare the different energy source consumptions, it was necessary to convert all the energy needs into primary energy by multiplying them by a primary energy conversion factor. According to Italian context, the conversion factor of electricity into primary energy was assumed to be equal to 2.17 [11].

3.1. Operation of shading and lighting systems

Two daylight sensor points were supposed positioned in the virtual test cell, both at the center line of the floor and both at 0.9m from floor level; one at 1/3 of the short side and the other at 2/3 of the short side (Fig.1(b)). They check the daylight illuminance level and the glare index and consequently control the operation of the shading and lighting systems.

The shading systems are activated every time the glare index exceeds the value of 19 [10]. They are also activated during cooling season when the solar irradiance hitting the window is more than 200 W/m^2. The lighting system was set to be switched on only during the occupation time and when the illuminance level of 500 lux isn't met by natural light. The electric power absorbed by the system was dimmed to get on balance with the targeted luminous flux. Each sensor point controls the operation of half of the luminaries.

3.2. Heating energy consumption calculation

Results of the dynamic simulation for sensible heating energy demand of each of the considered cases were reported in the first line of the following table. Primary energy consumption was calculated dividing the previous result by the heating system efficiency as shown in the following table. Then, in order to convert the energy consumption into primary energy source, a factor equal to 1 was assumed. This specific factor was selected because heating system fuel is gas.

Table 3. Heating primary energy calculation for analyzed systems

		BC	VB	EG
Sensible heating energy demand	(kWh/year)-(kWh/m^{3}year)	983.2 – (10.24)	1018.0 – (10.61)	1021.9 – (10.64)
Heating system efficiency	(-)	0.89	0.89	0.89
Primary energy conversion factor	(-)	1	1	1
Primary energy consumption	(kWh/year)-(kWh/m^{3}year)	1104.7 – (11.51)	1145.0 – (11.93)	1148.2 – (11.96)

The Base Case appears to have the lowest primary energy consumption for heating. This is reasonable because the BC can allow more solar heat gains due to its missing exterior shading controls. EG system causes the highest heating primary energy consumption for the opposite reason.

3.3. Cooling energy consumption calculation

Similarly to the heating case, the test cell was simulated over an year and the cooling energy demand for each system was calculated an reported in the first line of the following table. To convert cooling energy demand into primary energy consumption the heat pump efficiency was considered. A primary energy conversion factor for electricity was used for the conversion into primary energy.

Table 4. Cooling primary energy calculation for analyzed systems

		BC	VB	EG
Sensible cooling energy demand	(kWh/year)-(kWh/m^{3}year)	872.4 – (9.09)	714.3 – (7.44)	527.4 – (5.49)
Cooling system efficiency	(-)	2.5	2.5	2.5
Electricity consumption for cooling	(kWh/year)	349.0	285.7	210.9
Primary energy conversion factor	(-)	2.17	2.17	2.17
Primary energy consumption	(kWh/year)-(kWh/m^{3}year)	757.2 – (7.89)	620.0 – (6.46)	457.8 – (4.77)

Analyzing previous results, it can be noted that the EG system was responsible for the lowest primary energy consumption. It is lower than the BC by 39.54%, while the VB registered a decrement equal to

18.87% respect of BC's primary energy consumption. Comparing EG and VB results, it appears that the first one saved 26.16% of primary energy over the second one.

3.4. Lighting energy consumption calculation

Lighting energy needs are strictly related to shading system's capability to optimize daylighting on the work plane and avoid glare effects. So, lamps will be activated lamps to exactly cover the illuminance missing quota that can measured in the two sensor points described in 3.1 paragraph.

In the following table the electricity and primary energy consumptions for lighting are reported.

Table 5. Lighting primary energy calculation for both analyzed systems

		BC	VB	EG
Lighting electricity energy consumption	(kWh/year)-(kWh/m^{3}year)	494.5 – (5.11)	441.0 – (4.59)	334.9 – (3.49)
Primary energy conversion factor	(-)	2.17	2.17	2.17
Primary energy consumption	(kWh/year)-(kWh/m^{3}year)	1064.4 – (11.09)	957.0 – (9.97)	726.63 – (7.57)

From previous data, it can be noted that the EG system appears to be most efficient one, by allowing more natural light passing through and without compromising luminous comfort. The EG system saved a lighting primary energy equal to 32.28% over the BC result and equal to 24.06% over the VB one. VB system has a lower primary energy consumption of 10.82% compared to BC case.

A glare verification was also done. During the simulation time, both BC internal shade and the VB blinds never permitted a glare index on the work plane higher than 19, while the EG glazing turned out not always be able to avoid glare. The glare design value was overtaken few time, especially when Sun elevation angle was quite low.

3.5. Shading device consumption calculation

For the BC case a manual internal shading was assumed so no mechanical energy was needed to activate the device. To calculate energy consumption by positioning the VB device, an electric engine power equal to 160 W [12] was considered. This electric power was multiplied by the time needed to lift up or down the slats elements (about 10 seconds) every time the shading system was placed or removed. Typically, this operation happens twice a day in week days. Electric consumption due to rotation of slat elements was also considered, during the time in which shading device was positioned, assuming four rotations in an hour.

To calculate the electricity consumption for the EG operation, a power equal to 1.6 W/m^2 was considered during the time in which the system was active [6]. Simulation results are shown in the following table.

Table 6. Shading devices' operation primary energy consumption calculation for analyzed systems

		BC	VB	EG
Shading devices' electricity consumption	(kWh/year)-(kWh/m^{3}year)	-	0.454 - (0.005)	8.32 – (0.087)
Primary energy conversion factor	(-)	-	2.17	2.17
Primary energy consumption	(kWh/year)-(kWh/m^{3}year)	-	0.99 – (0.010)	18.04 – (0.188)

As can be observed, absolute values of shading devices' operation energy consumptions appear to be negligible in the whole energy balance because of its very low values. Nonetheless it could be noted that the primary energy consumption due to the EG activation was about 18 times higher than the one caused by VB operation.

3.6. Embodied energy calculation

The values of the embodied energy (EE) of the transparent components and their shading systems were calculated as shown in Table 7. In order to estimate this value for the EG coupled with a clear float glass, the embodied energy of a single clear glass was subtracted from the EE of a double low-e glazing and the EE of the EG glass was added. The embodied energy of the single EG glass was considered equal to 300 MJ/m^2 [11]. For the other materials, the IBO-Institute material database was considered [12].

Considering that the energy balance was done over an annual period, the calculated embodied energy (referred to the entire life span of the system) was linked to a yearly energy depreciation charge. Thus the embodied energy was divided by the estimated life span of the devices, equal to 20 years.

Table 7. Embodied energy calculation transparent components assumed for analyzed cases

Material description		Quantity			Unitary EE	Total embodied energy (kWh)		
		BC	VB	EG		BC	VB	EG
Low-emissive glazing		3.7 m^2	3.7 m^2	-	331 MJ/m^2	340.2	340.2	-
Electrochromic glazing		-	-	3.7 m^2	500 MJ/m^2	-	-	513.9
Aluminium frame		22.4 kg	22.4 kg	22.4 kg	84.4 MJ/kg	525.2	525.2	525.2
Fabric interior shade		1.0 kg	-	-	48.65 MJ/kg	13.5	-	-
Aluminium Venetian blind		-	15.0 kg	-	84.4 MJ/kg	-	351.7	-
Total	(kWh)					878.91	1217.1	1039.1
	(kWh/year)					43.94	60.86	51.95

Total embodied energy of the VB system appeared to be more than the EG and BC one. In particular it is 38.47% higher than the BC one and 17.13% higher than the EG one.

3.7. Comprehensive annual primary energy balances

First of all, the distribution over the year of sensible heating, sensible cooling and lighting electricity demands were summarized in the following graphs.

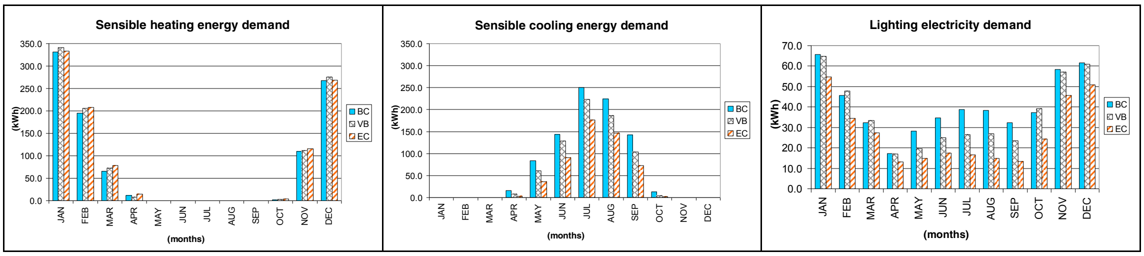

Fig.2. Sensible heating, sensible cooling and lighting electricity demands for analyzed systems

Then, primary energy consumption for different end uses of the three cases were summarized and compared in the following table in order to have a complete energy evaluation at a glance.

Table 8. Summary of primary energy needs for both analyzed cases, divided by end uses

Primary energy end use	BC	VB	EC	Absolute differences		Relative differences	
	(A)	(B)	(C)	(B) – (A)	(C) – (A)	[(B) – (A)]/(A)	[(C)–(A)]/(A)
Heating (kWh/year)	1104.7	1145.0	1148.2	+40.3	+43.5	+3.65%	+3.94%
Cooling (kWh/year)	757.2	620.0	457.8	-137.2	-299.4	-18.12%	-39.54%
Lighting (kWh/year)	1064.4	957.0	726.6	-107.4	-337.8	-10.09%	-31.74%
Shading device (kWh/year)	0.00	0.99	18.04	+0.99	+18.04	-	-
EE annual quota (kWh/year)	43.9	60.8	52.0	+16.92	+8.01	+38.50%	+18.45%
Total (kWh/year)	2970.2	2783.8	2402.6	-186.4	-567.6	-6.28%	-19.11%

It can be noted that EG presents the lowest energy balance mainly because of its capacity to save energy in cooling and lighting. The EG saved 19.11% respect to BC primary consumption and 13.69% respect to VB system. The VB system saved 6.28% respect to the BC primary energy consumption. Both VB and EC system have a better energy performance than the BC system. Their higher consumption in terms of heating (due to their behavior in reducing solar heat gains) and embodied energy are compensated by the other energy savings.

4. Economic evaluation

An economic balance of the analyzed shading systems was done. Firstly, the evaluation of their construction costs was done. Then, the systems were analyzed putting in comparison their costs including the gas and electricity operating costs. Note that all prices and costs applied were not taxes inclusive. Moreover, also installation and maintenance costs, which can be considered approximately equivalent, were not considered. Construction costs were derived from a public list delivered by the Municipality of Milano, Italy [15]. For the external aluminum venetian blind and for the electrochromic glazing, because of its particularity, some other specific cost sources were needed [12], [6]. In the following table, construction costs of analyzed systems were reported.

Table 9. Construction cost calculation for analyzed cases

Materials	Unitary cost	Quantity			Total cost		
		BC	VB	EG	BC	VB	EG
BC glazing	51.70 €/m^2	4.0 m^2		-	206.80 €		-
VB glazing	47 €/m^2		4.0 m^2			188 €	
EG glazing	828 €/m^2	-	-	4.0 m^2	-	-	3312 €
Th.- brake aluminium frame	288.76 €/m^2	4.0 m^2	4.0 m^2	4.0 m^2	1155.04 €	1155.04 €	1155.04 €
Fabric internal shade	100 €/m^2	4.0 m^2	-	-	400€	-	-
Aluminium venetian blind	125 €/m^2	-	4.0 m^2	-	-	500 €	-
Total					1761.84 €	1843.04 €	4467.04 €

As mentioned above, the gas consumption for heating was calculated. The thermal system energy input was divided by the methane gas calorific value (assumed equal to 9.77 kWh/Nm^3). Then, the annual gas consumption was multiplied by a mean national unitary gas cost, equal to 0.65 €/Nm^3 [16]. Electric consumption were multiplied by an average national price equal to 0.08703 €/kWh [16]. Results are shown in the following table.

Table 10. Annual energy operating costs distinguished by end uses for the three analyzed cases

Energy consumpt. end use	Gas consumption [m^3]			Electricity consumption [kWh]			Energy price	Energy consumption cost [€]		
	BC	VB	EG	BC	VB	EG		BC	VB	EG
Heating gas cons.	113.1	117.2	117.5	-	-	-	0.65 €/m^3	75.30	76.17	76.39
Cooling electricity consumption	-	-		349.0	285.7	210.9	0.08703 €/kWh	30.37	24.87	18.36
Lighting electricity consumption	-	-		490.5	441.0	334.9	0.08703 €/kWh	42.69	38.38	29.15
Shading operation electricity cons.	-	-		0.00	0.454	8.3	0.08703 €/kWh	0.00	0.04	0.72
Total	113.1	117.2	117.5	839.5	727.2	554.1		146.56	139.46	124.62

From this computation it can be noted that the EG system saved annually €21.91 with respect to BC (corresponding to 14.95% of BC's total annual energy consumption cost), and €14.84 respect to the VB case (corresponding to 10.64% of its total annual energy consumption cost). Even if annual energy consumption costs are very similar, EG have a significant economic impact, with an extra-cost equal to €2705.20 with respect to BC and equal to € 2614.00 with respect to VB.

The economic comparison was done evaluating the net present value of the three analyzed systems over the component's life span (20 years), assuming a constant rate of interest equal to 4% and an annual increase of energy cost equal to 5%. In the following graph, the results of this calculation are shown and compared.

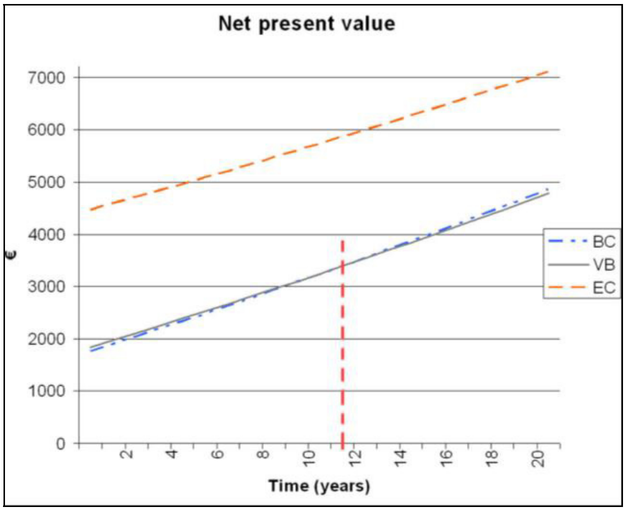

Fig.3. Net present value for the three analyzed systems

As can be noted in Fig.3, EG solution, although allowing a certain energy saving, is not competitive from the strictly economic point of view because of its very high initial cost with respect to the other two configurations. VB system, starts to be more economically convenient than BC between the 11th and 12th year.

5. Conclusions

We demonstrated that external solar control systems really involve better overall energy performance than a glazing system without external shading devices. In particular, among the compared systems, the EG resulted to be the most efficient one from the primary energy consumption point of view. However, at present day, it appears to be not affordable mainly because of its high purchasing cost. VB system appears to be a good intermediate solution, that causes more primary energy consumption than EG configuration, but less then BC, and has a construction cost quite similar to BC one. By the way, it has to be considered that environmental damages caused by CO_2 emissions in atmosphere have a cost too. In particular, assuming a CO_2 equivalent mass emission factor equal to $0.1998kgCO_{2eq}$ for gas consumption and equal to $0.4332kgCO_{2eq}$ for electricity consumption [17], EG and VB, as assumed in this study, causes an emission saving, with respect to BC, respectively equal to 19.12% and equal to 6.95%.

References

[1] D.Lgs. 19 /08/ 2005, n. 192"Attuazione della direttiva 2002/91/CE relativa al rendimento energetico nell'edilizia".

[2] Energy Performance Building Directive Recast 2010/31/CE, adopted on 19 May 2010 .

[3] Lee E, Selkowitz SE. The New York Times Headquarters daylighting mockup: Monitored performance of the daylighting control system. Energy & Buildings no, 38; 2006, p. 914-929.

[4] http://apps1.eere.energy.gov/buildings/energyplus/weatherdata_sources.cfm.

[5] Aste N, et al. The influence of the external walls thermal inertia on the energy performance of well insulated buildings. Energy and Building, no. 41; 2009, p. 1181-1187.

[6] Lawrence Berkeley National Laboratory, "A design guide for early-market Electrochromic windows", 2006

[7] International Glazing Database (IGDB).

[8] UNI/TS 11300-1:2008 – "Prestazioni energetiche degli edifici - Parte 1: Determinazione del fabbisogno di energia termica dell'edificio per la climatizzazione estiva ed invernale".

[9] UNI 10339:1995 – "Impianti aeraulici al fini di benessere".

[10] Szokolay S. V., Introduction to Architectural Science: The Basis of Sustainable Design, Elsevier/Architectural Press, 2008

[11] Art. 2 comma 3, D.M. 20/07/2004: "Nuova individuazione degli obiettivi quantitativi per l'incremento dell'efficienza energetica negli usi finali di energia, ai sensi dell'art. 9, comma 1, del D.Lgs. 16 marzo 1999, n. 79".

[12] CDR Building Solutions technical documentation, 2012

[13] Syrrakou E, et al. Environmental assessment of electrochromic glazing production. Solar Energy Materials & Solar Cells, no. 85; 2005, p. 205-240.

[14] Österreichisches Institut für Baubiologie und Bauökologie, IBO-Richtwerte für Baumaterialien.

[15] Comune di Milano – Area territorio, "Listino dei prezzi per l'esecuzione di opere pubbliche e manutenzioni", 2012.

[16] Autorità per l'energia elettrica e il gas, "Relazione annuale sullo stato dei servizi e sull'attività svolta", 2011.

[17] Piano d'Azione per l'Energia della Regione Lombardia D.G.R. VIII/4916, 2008.