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The Energy Saving Potential of Wide Windows in Hospital Patient Rooms, Optimizing the Type of Glazing and Lighting Control Strategy under Different Climatic Conditions

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Abstract: If not properly designed, the adoption of large windows can sometimes have a negative impact on building energy demand. For this reason, aggravated by the outdated building envelope of the healthcare building stock, large fenestration systems are usually avoided in hospitals, especially in old structures. However, with appropriate glazing specifications, the adoption of wider openings can result into significant energy savings, lower costs and strong positive effects on patients and staff well-being. The present study investigates how different window sizes and types of glazing affect heating, cooling and lighting energy demand in a hospital patient room. The objective is to evaluate the energy savings that may be obtained when installing larger windows and to identify the glazing properties allowing one to reach the maximum energy reductions. Simulations were carried out using nine diverse glazing systems, already available on the market, and their energy performance was evaluated in relation to two different window areas: a common size opening, characterized by a 25% Window-to-Wall Ratio (WWR), and a floor to ceiling window, with 77% WWR. The analysis was conducted taking into consideration four different orientations in four Italian cities, supposing two artificial lighting control strategies. The results highlighted how the adoption of wider windows with appropriate glazings and a daylight-linked dimming lighting control strategy may lower the primary energy demand up to 17%.

Keywords: energy demand; hospital patient rooms; window-to-wall ratio (WWR); glazing specifications; lighting; dynamic building energy simulations; TRNSYS

1. Introduction

Among the three macro-areas in which regulation and scientific literature distinguish hospital spaces [1–5]—Inpatient Units (IPUs), Diagnostic and Treatment Facilities (D&T) and nonclinical spaces or general services—IPUs are characterized by less high-tech, energy intensive areas and medical equipment than D&T Facilities.

However, albeit spaces for IPUs have been decreasing in favor of those occupied by general services, IPUs still represent a significant percentage of the conditioned floor area in old existing hospitals. Providing healthcare services 24/7, patient rooms are characterized by massive heating and cooling energy consumption, due to the necessity of high ventilation rates and their stricter requirements for microclimatic control. Furthermore, being located in the perimeter areas of the building to ensure maximum natural light, patient rooms present the highest part of external surface, along with connective spaces [6]. This factor is one of the elements contributing to the significant energy use of IPUs and its negative impact is proportional to the level of obsolescence of the building envelope. To understand the influence of building obsolescence, it is important to highlight that in Italy, as in most other European countries, about 60% of the healthcare facilities were built before 1980 [7,8].

Being one of the most vulnerable elements of the building envelope, windows have usually represented a critical aspect in architectural design as, if not properly conceived, they can sometimes have a negative impact on the building energy needs. For this reason, large openings have been often avoided. However, with a proper building design, the adoption of wider fenestration systems can translate into significant energy savings and occupant comfort improvement, thus reducing operating and investment costs and increasing hospital resilience. When provided with low-emission coatings, larger windows allow one to cut heat losses during the heating period, and the application of solar selective films enables one to lower the cooling load due to solar radiation. Furthermore, with a greater availability of natural light, artificial lighting energy consumption may be reduced up to 25%, with a decrease in maintenance costs associated with lamp replacement [9].

On the other hand, a well-designed daylighting is extremely useful not only from an energy performance perspective. A large number of studies have shown that natural brightness and outside views are important to improve the health of patients and hospital staff, highly increasing their psychophysical well-being [10–17]. Patients exposed to significant daylight are characterized by less suffering, thus requiring less drugs for pain relief [18]. Indeed, natural light promotes serotonin production and vitamin D synthesis. The former contributes to alleviate pain feeling, while the latter, if lacking, may cause musculoskeletal suffering [19,20]. Similar findings were demonstrated by Ulrich in 1984, who noticed that patients with views to nature were characterized by a lower Average Length of Stay (ALOS) if compared with those ones with just a view of neighboring buildings [21]. The benefit of an exposure to daylight has been studied also for people with depression [22–27] and related with a lower death rate in patients affected by cardiovascular diseases or cancer [28,29]. As regards hospital staff, they shown an improved alertness, less stress and were found to be more satisfied with their job [30,31].

Moreover, the increased daylight availability in hospital patient rooms, by lowering energy use, improving efficacy of healthcare delivery and shortening patient ALOS [21,32–34], allows one to significantly cut healthcare expenditures [9,18] (equal to about €162 per patient in Italy) [35], with highly positive impacts on the economic sustainability of hospitals.

In 2016 the global health expenditure accounted for roughly 10% of the Gross Domestic Product (GDP), with the United States spending the most of any nation by far on its healthcare system (17.1%) [36]. Considering Italy, the country national health service expenditures have increased of about 30% in the last twenty years, reaching 8.9% of GDP [36] and requiring resources that could have been used for other healthcare purposes. Therefore, hospital budgets getting tighter and political pressure reducing healthcare expenditures underline the need of forecasting and assessing this energy and cost saving potential.

The majority of studies on this topic focuses on the positive effects of windows on building occupants' well-being, but rarely investigates the role of glazing types, size and orientation as well as their effects on building energy use.

A large amount of literature examined the beneficial effects of daylight on people working in offices [37–39], some of these also took into account the impact of diverse window sizes, quantity, and distribution [40]. Indeed, research results demonstrated that windows characterized by 20%–25% Window-to-Wall Ratio (WWR) were considered too small, while openings with WWR higher than 30%–35% were perceived to be too large [41,42]. Several works analyzed how exposure to natural light may positively impact on children health and improve their learning progress [43,44].

Despite this huge set of topics deeply investigated by literature, only very few studies focused on the relation between window size and patient satisfaction, that seems to be achieved when window area occupies 20%–30% of the external wall [45], while only some recent approaches took into consideration window orientation, from which it strictly depends the amount of solar radiation entering the space, thereby the amount of solar heat gain, thermal losses and daylight. Choi et al. observed that patients hospitalized in rooms facing south-east had 16%–41% shorter ALOS compared to patients in north-west oriented rooms [33]. Likewise, Benedetti et al. found that exposure to east daylight may reduce ALOS by about 3.67 days compared to access to natural light coming from the west [34].

Some works examined windows with diverse dimensions, orientation and glazing properties [46,47] in residential buildings [48–51], in a lecture room [52] and in office buildings [53–58], while Sarbu and Sebarchievici [59] reported the relation between the window height, U-value, outdoor air temperature and air velocity were able to ensure local thermal comfort.

Several software tools are available for assessing the influence of windows on building energy consumption, like EFEN, using EnergyPlus simulation engine [60], COMFEN, developed by Lawrence Berkeley National Laboratory [61] and MIT Design Advisor by the Massachusetts Institute of Technology (MIT) School of Architecture and Planning [62].

However, only a limited number of works conducted a comprehensive analysis of the impact of window size, orientation and kinds of glazing on patient rooms energy use, hampering the development of a reliable and exhaustive benchmark dataset. Cesari et al. [63] focused on the impact of these variables on heating and cooling energy needs by adopting wider openings, without analyzing the energy savings achievable on lighting energy demand. Furthermore, the study [63] did not evaluate glazing energy performance under different climatic conditions.

The present work aimed at assessing and comparing the influence of windows with diverse dimensions and glazing properties on the energy demand of a hospital patient room under different orientations and four climatic conditions. The objective was to evaluate the energy savings that can be obtained when larger windows are preferred and to identify the glazing specifications allowing one to reach the maximum energy reductions.

The analysis was conducted on the basis of the energy model of the whole hospital facility and focused on the patient room energy demand with the purpose of achieving the most robust results. The final purpose was to build a reliable reference dataset that may also assist architects and engineers in identifying the most effective glazing solutions when renovating a hospital building, as well as to pave the base to new hospital standards.

2. Structure of the Method of Analysis

As reported by the studies reviewed above, with proper building design, the adoption of windows with appropriate glazing specifications may drastically reduce the energy needs and costs related to the patient room, and, particularly, its building envelope, while increasing patient comfort.

Albeit window properties like the U-value and g-value are provided by manufacturers, energy saving interventions involving the building envelope require to consider the interaction and variation of different features, like occupancy schedules, morphological aspects of the building, operating hours, both indoor design and outdoor thermo-hygrometric conditions, control systems, etc.

Dynamic building energy simulation software is used to analyze the savings achievable on building energy use while taking into account different variables [64–67], as well as their environmental impact [68–72].

In the present study, the dynamic building energy simulation program TRNSYS was used to calculate and compare the sensible energy needs for heating and cooling and the artificial lighting energy demand of a hospital patient room in relation to the following variables:

- Glazing types;
- Window sizes;
- Room orientations;
- Climatic conditions;
- Lighting control strategies.

Considering the beneficial effects of wider windows and daylight reported by the literature reviewed above, this work investigates the effects of larger openings on patient room energy needs.

The analysis focused only on the sensible energy demand since window area, orientation and kind of glazing do not impact on latent loads [73].

The building volume was modelled with TRNSYS3D plugin for Google Sketchup, while all the non-geometry information like layer material properties, ventilation and infiltration profiles, heat gains, etc. were added in TRNBuild. The characteristics defined were saved in text files, which were then read by Type 56 during simulations carried out in Simulation Studio [74,75].

The multizone building model Type 56 calculates the energy balance as the convective and conductive heat flux to the air node defined by the following equation:

$$\dot{Q}_i = \dot{Q}_{surf,i} + \dot{Q}_{inf,i} + \dot{Q}_{vent,i} + \dot{Q}_{g,c,i} + \dot{Q}_{cplg,i} \quad (1)$$

where $\dot{Q}_i$ is the conductive and convective heat flux, $\dot{Q}_{surf,i}$ are the convective gains from surfaces, $\dot{Q}_{inf,i}$ are the infiltration gains (air flow from outside only), $\dot{Q}_{vent,i}$ are the ventilations gains, $\dot{Q}_{g,c,i}$ are the internal convective gains (by people, equipment, illumination, radiators, etc.) and $\dot{Q}_{cplg,i}$ are the gains related to convective air flow coming from adjacent thermal zones, while radiative heat flows to the walls and windows are defined as:

$$\dot{Q}_{r,w_i} = \dot{Q}_{g,r,i,w_i} + \dot{Q}_{sol,w_i} + \dot{Q}_{long,w_i} + \dot{Q}_{wall-gain} \quad (2)$$

where $\dot{Q}_{r,w_i}$ are the radiative gains for the wall surface temperature node, $\dot{Q}_{g,r,i,w_i}$ are the radiative air node internal gains received by walls, $\dot{Q}_{sol,w_i}$ represents the solar gains through windows received by walls, $\dot{Q}_{long,w_i}$ is the long wave radiation exchange between a wall and all the other walls and windows and $\dot{Q}_{wall-gain}$ is the user-specified heat flow to the wall or window surface. The unit of measure of the terms in Equations (1) and (2) is kJh^{-1}.

Weather data of the four cities considered in the analysis were provided by Meteonorm database and weather stations, and are reported in the external text files read by Type 15 in Simulation Studio to evaluate gains from solar radiation [74].

Case Study

A typical hospital building representative of the Italian healthcare building stock was taken as a case study. Its characteristics were determined on the basis of the investigation reported in reference [6]. The hospital was supposed to be located in four Italian cities, Milan, Bologna, Rome and Naples, in order to analyze the room energy needs under different climate conditions.

Milan and Bologna have a humid subtropical climate (Cfa) [76], which is the most prevalent climate in Italy along with the hot-summer Mediterranean type (Csa), also typical of a wide area of the South-Eastern United States, South-Eastern South America, Eastern Asia and Eastern Australia. The cities of Rome and Naples were selected to represent the hot-summer Mediterranean type (Csa). Geographical and climatic characteristics of the cities analyzed are reported in Table 1.

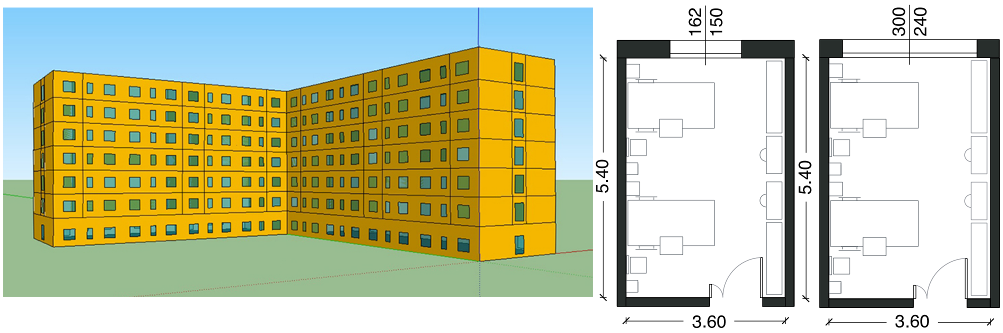
Table 1. Climatic characteristics of the cities analyzed.

City	Altitude (m)	HDD (°C Day) Baseline: 20 °C [77]	CDD (°C Day) Baseline: 26 °C [77]	Annual GSR [1] on the HP [2] ($kWhm^{-2}$) [78]	Climatic Vector Vc [79,80]	Köppen Climate Classification [76]	Heating Period
Milan	122	2404	31	1345	0.312	Cfa	15 October–15 April
Bologna	54	2259	61	1420	0.357	Cfa	15 October–15 April
Rome	20	1415	38	1562	0.408	Csa	1 November–15 April
Naples	17	1034	74	1589	0.516	Csa	15 November–31 March

[1] Global solar radiation. [2] Horizontal plane.

The case study consisted of two linear volumes composed of seven floors and arranged perpendicular to each other in the shape of an L (Figure 1a). The facility has a covered area of 1196 m^2 and a total conditioned floor area of 6680 m^2, with a surface to volume ratio (S/V) equal to 0.41.

Simulations were conducted to assess the energy demand for space heating, cooling and lighting of a patient room situated on the third floor and facing no external obstruction. Volume and external area of the tested two-bed room were supposed to be 52.5 m^3 and 7.3 m^2 respectively. Being representative of the state of the Italian healthcare building stock, a building envelope with a very poor energy performance was assumed, with a thermal transmittance of the external wall of 1.40 $Wm^{-2}K^{-1}$. The floor plan and dimensions of the tested room are shown in Figure 1b,c.



(**a**) (**b**) (**c**)

Figure 1. Perspective view of the hospital case study (**a**) and floor plans of the patient room with the two window sizes analyzed: 25% WWR window (**b**) and 77% WWR window (**c**).

The tested room, as well as the whole facility, is provided with an air conditioning system with 24/7 operation schedule [9,81]. A ventilation load of 1056 MWh was considered. Indoor design thermohygrometric conditions, air infiltration rate and internal loads are reported in Table 2. The longwave emission coefficient of walls, ceiling and floor were assumed to be 0.9.

Table 2. Temperature and relative humidity set-points, air infiltration rate and internal loads of the room.

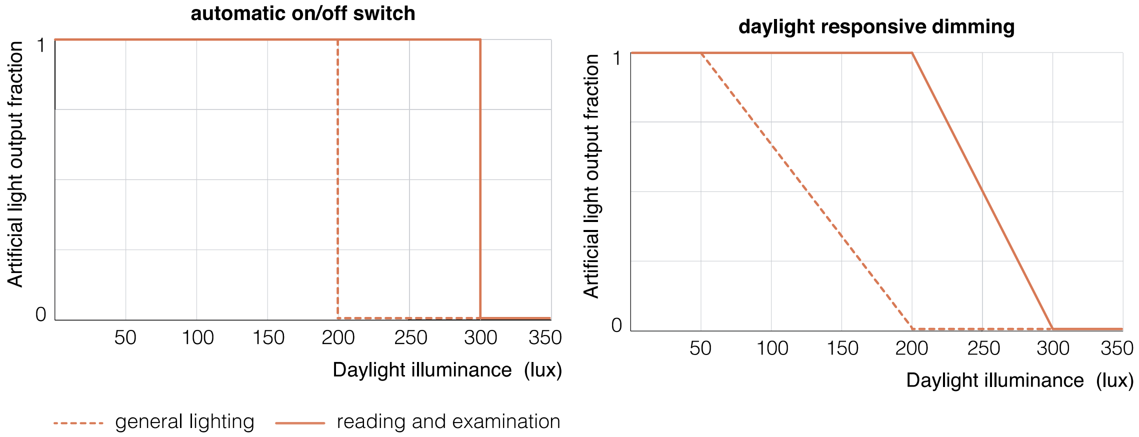
Temperature Set-Point (°C)		**Relative Humidity (%)**	**Air Infiltration Rate ($volh^{-1}$)**	**Internal Loads Sensible Heat [82]**	
Winter	**Summer**			**Patients (W)**	**Lamps (Wm^{-2})**
22	26	50	2.0	120	7.4

The room was equipped with two recessed fluorescent lamps, 54 W each, for general lighting. In addition, two bed head units were installed, providing each bed with one 36 W fluorescent lamp for general lighting and two 18 W fluorescent lamps for reading and simple examination. The system was able to ensure a higher illuminance level than the minimum required by the standards, i.e., 100 lux for general lighting and 300 lux for reading and simple examination, measured at 0.03 m and 0.90 m above the floor respectively, as defined by UNI EN 12464-1:2011 regulation [83]. Considering that the two 54 W recessed fluorescent lamps are more than sufficient to meet the regulatory requirements for general lighting [83], and that the two 36 W lamps for general lighting and two of the fours 18 W lamps for reading and simple examination installed in the bed head units were turned on for a short period of time for medical needs, these lamps in the bed head units were not included in the evaluation. As the aim of the work was to analyze different types of glazing, the study does not consider the contribution of these lamps because their use does not depend on the glazing type, but it is due to the need of the medical staff to have additional lighting. The other two 18 W fluorescent lamps installed in the two bed head units for reading were assumed to be turned on for a limited period of time during the day (4 h). The related heat gains were assumed to be equal to the installed power for lighting, that is 7.4 Wm^{-2} (Table 2), distributed between radiative and convective fraction according to the following shares: for recessed fluorescent lamps, 70% radiative fraction and 30%

convective fraction; for fluorescent lamps included in bed head units, 50% radiative fraction and 50% convective fraction, as reported by ASHRAE [84].

Artificial lighting was supposed to be on from 07.00 am to 09.00 pm. In order to take full advantage of the beneficial effects of wider windows and, more in detail, of their contribution in maximizing energy savings, two lighting control systems were analyzed: an automatic on/off switch and a daylight-linked dimming control (Figure 2a,b). Indeed, studies available in literature have demonstrated that dimmable lighting control strategy dependent on daylight illuminance reduce lighting and cooling energy demand, allowing to achieve energy savings up to 40% [85–90].

The analysis considered two window dimensions: a common size opening, having an area of 2.43 m² (1.62 m wide per 1.5 m height), equal to 25% WWR (Figure 1b); a floor to ceiling window, with an area of 7.2 m² (3.0 m wide per 2.4 m height), equal to 77% WWR (Figure 1c).



(**a**) (**b**)

Figure 2. Definition of the two lighting control strategies analyzed according to the illuminance level required for general lighting and reading and examination.

The wider window was supposed to be provided with a dynamic external shading device. Indeed, a growing body of literature [56–57,91] has demonstrated that dynamic shading systems allow one to achieve the best energy savings and visual comfort compared to fixed solar shadings and the advantages of external screens (commonly used) have been widely investigated [57,92].

The control of the shading devices was defined in order to activate the system only during the cooling period and leave exposed 1.2 m² of the window area to the sun when solar radiation incident on the window exceeded about 150 Wm⁻² (100 Wm⁻² for a south-orientated façade and 200 Wm⁻² for a west or east-exposed façade), 0.6 m² when solar radiation exceeded 400 Wm⁻² (for a north-exposed façade) [57] and 0.3 m² from 14.00 to 16.00 pm, when drowsiness level of patients as well as ordinary people is higher during the day [93–99].

In view of the goal of this study, nine glazing systems with different U-values, g-values and visible transmittance (Tvis) were selected (data are reported in Table 3). All the glazing solutions were assumed to be provided with a frame having a thermal transmittance of 2.3 Wm⁻²K⁻¹.

Table 3. Glazing types specifications.

g-Value (Dimensionless)	U-Value ($Wm^{-2}K^{-1}$)	Tvis (Dimensionless)	Composition
0.79	2.89	0.75	4/12/4
0.57	1.40	0.77	44.2/14/44.4
	1.10	0.77	44.2/16/44.4
0.46	1.40	0.69	44.2/14/44.4
	1.10	0.69	44.2/14/44.4
	0.70	0.69	44.2/16/4/16/44.4
0.40	1.40	0.66	44.2/14/44.4
	1.10	0.66	44.2/14/44.4
	0.70	0.66	44.2/16/4/16/44.4

In order to conduct a robust and reliable analysis, developed on the basis of the most realistic conditions, the selection of the glazing systems analyzed was made with the support of the technical department of two leading flat glass manufacturers.

The following criteria were considered:

- Compliance with regulatory thermal [100], safety [101] and acoustic [102] requirements;
- Commercial availability (the case study with a g-value of 0.57 and U-value of 0.70 $Wm^{-2}K^{-1}$ was not investigated as it is not available on the market);
- Capacity to ensure the g-values, U-values and Tvis values selected by avoiding complex solutions and unnecessary costs when a more reasonable solution was available.

The Italian standard Decree 26/06/2015 [100] appoints specific limit values of window thermal transmittance in case of building energy refurbishment for the different Italian climate zones, as reported in Table 4. The regulatory threshold limit refers to the thermal transmittance of the whole fenestration system, composed by the glazing, the frame and the shutter box, and it is named as Uw-value. Regulation requires to comply with the defined standards from 1 January 2021.

Table 4. Regulatory limit values of thermal transmittance of the fenestration system in building energy refurbishment.

Climate Zone	Uw-Value ($Wm^{-2}K^{-1}$)
A and B	3.0
C	2.0
D	1.8
E	1.4
F	1.0

Although regulation allows one to use an Uw-value higher than 1.4 $Wm^{-2}K^{-1}$ for climate zones A, B, C and D, the size of window profiles currently commercially available brings to use a Uw-value of about 1.4 $Wm^{-2}K^{-1}$ also for these climate zones. An Uw-value higher than 1.4 $Wm^{-2}K^{-1}$ requires smaller window profiles, which are no longer available.

The Italian standard UNI 7697:2015 [101], which regulates the installation of safety glazing in healthcare environments, requires a toughened or laminated glass outside and a laminated glass inside, according to a specific level of impact resistance [103], as reported in Table 5.

Table 5. Classes of impact resistance required by regulation for safety glass application in hospitals.

Risk	External Glass Sheet		Internal Glass Sheet
	Toughened	**Laminated**	**Laminated**
damage to people	1C3 [1]	2B2 [2]	2B2
falling into the void	1C3	2B2	1B1 [3]
		1B1	2B2

[1] Resists an impact from a fall height of 190 mm without breaking. [2] Resists an impact from a fall height of 450 mm without allowing penetration. [3] Resists an impact from a fall height of 1200 mm without allowing penetration.

The necessity to use toughened or laminated glass requires panes with significant thickness, which limits g-value to maximum 0.60.

The selected glazing systems were generated by means of WINDOW 7.5 [104], a software developed by the Lawrence Berkeley National Laboratory for calculating total window thermal performance indices. For each system, the specific glass types and gaps composing it (with the related specification, like the product name, manufacturer, color, thickness, visible and solar transmittance, visible and solar reflectance, conductivity, etc.) were selected from the international library included in the software. The program then calculated the performance data using updated algorithms consistent with ASHRAE SPC142 [105], ISO 15,099 [106] and generated a report (text file) containing all the window specifications (U-value, g-value, visible transmittance, relative heat gain, shading coefficient, etc.), in a format that may be added to the TRNBuild glazing library and then used by TRNSYS to calculate heating, cooling and lighting energy needs.

The glazings were analyzed for each window size, room orientation, lighting control strategy and city taken into consideration (Table 6), for a total number of 528 scenarios.

Table 6. Summary of the scenarios analyzed for each of the four cities considered, Milan, Bologna, Rome and Naples.

n.	g-Value (Dimensionless)	U-Value ($Wm^{-2}K^{-1}$)	WWR (%)	Orientation	Lighting Control Strategy
1	0.79	2.89	25	W	automatic on/off
2				E	automatic on/off
3				S	automatic on/off
4				N	automatic on/off
5	0.57	1.40	25	W	automatic on/off
6					dimming
7				E	automatic on/off
8					dimming
9				S	automatic on/off
10					dimming
11				N	automatic on/off
12					dimming
13			77	W	automatic on/off
14					dimming
15				E	automatic on/off
16					dimming
17				S	automatic on/off
18					dimming
19				N	automatic on/off
20					dimming
21	0.57	1.10	25	W	automatic on/off
22					dimming
23				E	automatic on/off
24					dimming
25				S	automatic on/off
26					dimming
27				N	automatic on/off
28					dimming
29			77	W	automatic on/off
30					dimming
31				E	automatic on/off
32					dimming
33				S	automatic on/off
34					dimming
35				N	automatic on/off
36					dimming
37	0.46	1.40	25	W	automatic on/off
38					dimming
39				E	automatic on/off
40					dimming
41				S	automatic on/off
42					dimming
43				N	automatic on/off
44					dimming
45			77	W	automatic on/off
46					dimming
47				E	automatic on/off
48					dimming

49				S	automatic on/off
50					dimming
51				N	automatic on/off
52					dimming
53	0.46	1.10	25	W	automatic on/off
54					dimming
55				E	automatic on/off
56					dimming
57				S	automatic on/off
58					dimming
59				N	automatic on/off
60					dimming
61			77	W	automatic on/off
62					dimming
63				E	automatic on/off
64					dimming
65				S	automatic on/off
66					dimming
67				N	automatic on/off
68					dimming
69	0.46	0.70	25	W	automatic on/off
70					dimming
71				E	automatic on/off
72					dimming
73				S	automatic on/off
74					dimming
75				N	automatic on/off
76					dimming
77			77	W	automatic on/off
78					dimming
79				E	automatic on/off
80					dimming
81				S	automatic on/off
82					dimming
83				N	automatic on/off
84					dimming
85	0.40	1.40	25	W	automatic on/off
86					dimming
87				E	automatic on/off
88					dimming
89				S	automatic on/off
90					dimming
91				N	automatic on/off
92					dimming
93			77	W	automatic on/off
94					dimming
95				E	automatic on/off
96					dimming
97				S	automatic on/off
98					dimming
99				N	automatic on/off
100					dimming
101	0.40	1.10	25	W	automatic on/off
102					dimming
103				E	automatic on/off
104					dimming
105				S	automatic on/off
106					dimming

107				N	automatic on/off
108					dimming
109			77	W	automatic on/off
110					dimming
111				E	automatic on/off
112					dimming
113				S	automatic on/off
114					dimming
115				N	automatic on/off
116					dimming
117	0.40	0.70	25	W	automatic on/off
118					dimming
119				E	automatic on/off
120					dimming
121				S	automatic on/off
122					dimming
123				N	automatic on/off
124					dimming
125			77	W	automatic on/off
126					dimming
127				E	automatic on/off
128					dimming
129				S	automatic on/off
130					dimming
131				N	automatic on/off
132					dimming

3. Results and Discussion

The results obtained by simulations were outlined in the following lines, where energy needs for heating, cooling and lighting converted into primary energy demand (PED) were reported. For the conversion it was assumed a global efficiency of the heating system (powered by natural gas boiler) equal to 0.68, assessed by considering all the efficiencies values of the system (emission and control, distribution and generation) [107]; the average efficiency of the electricity production system in Italy, equal to 0.46 [108–110]; a conversion factor of 0.92 for cooling energy demand, obtained from the product between the emission and control efficiency, the distribution efficiency of the system, an energy efficiency ratio EER for the electric chiller of 2.7 and the average efficiency of the national electricity production system.

A first analysis of the data expressed in absolute values (reported in Appendix A for the sake of brevity) underlines that heating primary energy needs were decisively the main contributors to the primary energy demand of the patient room, being responsible for about 82% (88% in Milan, 85% in Bologna, 80% in Rome and 77% in Naples), followed by lighting and cooling primary energy needs, equal to about 11% and 7% respectively.

The percentage changes in heating (PED_H), cooling (PED_C), lighting (PED_L) and total (PED_T) primary energy demand of the patient room analyzed for the city of Milan (Table 7), Bologna (Table 8), Rome (Table 9) and Naples (Table 10) are reported below.

As energy needs were found to vary between the four different orientations with a very similar trend for all the glazing types examined, a further analysis focused only on the results obtained for the 77% WWR window facing west. Only findings regarding west-facing glazings were further examined as this orientation allows us to achieve the maximum savings both on heating and cooling energy needs. Moreover, taking into account the obsolescence level of the majority of the healthcare building stock, the scenario with a 25%WWR window characterized by a U-value of 2.89 $Wm^{-2}K^{-1}$ and a g-value of 0.79 was considered symbolic of the state of most existing hospitals in Italy. Therefore, this condition was assumed the reference condition against which to benchmark potential energy savings, and it was called the "base case" scenario.

Table 7. Percentage change in primary energy demand for heating, cooling and lighting evaluated for each glazing type and lighting control strategy compared to the base case in Milan.

Milan							
g-Value (Dimensionless)	**U-Value ($Wm^{-2}K^{-1}$)**	**WWR (%)**	**Lighting Control Strategy**	**ΔPED_H (%)**	**ΔPED_C (%)**	**ΔPED_L (%)**	**ΔPED_T (%)**
0.79	2.89	25	automatic on/off	base case	base case	base case	base case
0.57	1.40	77	automatic on/off	−9	−21	−16	−10
			dimming	−7	−25	−51	−13
	1.10	77	automatic on/off	−11	−19	−16	−12
			dimming	−9	−23	−51	−15
0.46	1.40	77	automatic on/off	−5	−35	−15	−8
			dimming	−3	−39	−50	−10
	1.10	77	automatic on/off	−8	−34	−15	−10
			dimming	−6	−38	−50	−13
	0.70	77	automatic on/off	−12	−32	−14	−14
			dimming	−10	−36	−50	−16
0.40	1.40	77	automatic on/off	−2	−41	−14	−6
			dimming	−1	−45	−50	−9
	1.10	77	automatic on/off	−5	−41	−14	−8
			dimming	−4	−45	−50	−11
	0.70	77	automatic on/off	−10	−38	−14	−12
			dimming	−9	−42	−50	−15

Table 8. Percentage change in primary energy demand for heating, cooling and lighting evaluated for each glazing type and lighting control strategy compared to the base case in Bologna.

Bologna							
g-Value (Dimensionless)	**U-Value ($Wm^{-2}K^{-1}$)**	**WWR (%)**	**Lighting Control Strategy**	**ΔPED_H (%)**	**ΔPED_C (%)**	**ΔPED_L (%)**	**ΔPED_T (%)**
0.79	2.89	25	automatic on/off	base case	base case	base case	base case
0.57	1.40	77	automatic on/off	−6	−22	−15	−9
			dimming	−2	−26	−50	−10
	1.10	77	automatic on/off	−9	−20	−15	−11
			dimming	−5	−24	−50	−12
0.46	1.40	77	automatic on/off	−2	−35	−14	−7
			dimming	2	−39	−50	−8
	1.10	77	automatic on/off	−6	−34	−14	−9
			dimming	−1	−38	−50	−10
	0.70	77	automatic on/off	−10	−33	−14	−13
			dimming	−6	−37	−49	−14
0.40	1.40	77	automatic on/off	0	−42	−13	−5
			dimming	4	−45	−49	−6
	1.10	77	automatic on/off	−3	−41	−13	−8
			dimming	1	−45	−49	−9
	0.70	77	automatic on/off	−8	−39	−13	−11
			dimming	−4	−42	−49	−13

Table 9. Percentage change in primary energy demand for heating, cooling and lighting evaluated for each glazing type and lighting control strategy compared to the base case in Rome.

Rome							
g-Value (Dimensionless)	**U-Value (Wm^{-2}K^{-1})**	**WWR (%)**	**Lighting Control Strategy**	**ΔPED_H (%)**	**ΔPED_C (%)**	**ΔPED_L (%)**	**ΔPED_T (%)**
0.79	2.89	25	automatic on/off	base case	base case	base case	base case
0.57	1.40	77	automatic on/off	−11	−22	−12	−12
			dimming	−6	−27	−48	−15
	1.10	77	automatic on/off	−15	−20	−11	−15
			dimming	−10	−25	−47	−17
0.46	1.40	77	automatic on/off	−3	−36	−10	−7
			dimming	3	−41	−47	−10
	1.10	77	automatic on/off	−7	−35	−10	−10
			dimming	−1	−40	−47	−12
	0.70	77	automatic on/off	−12	−33	−10	−14
			dimming	−7	−38	−47	−16
0.40	1.40	77	automatic on/off	2	−43	−9	−5
			dimming	8	−47	−46	−7
	1.10	77	automatic on/off	−2	−42	−9	−7
			dimming	3	−46	−46	−10
	0.70	77	automatic on/off	−8	−39	−9	−12
			dimming	−3	−44	−46	−14

Table 10. Percentage change in primary energy demand for heating, cooling and lighting evaluated for each glazing type and lighting control strategy compared to the base case in Naples.

Naples							
g-VALUE (Dimensionless)	**U-Value (Wm^{-2}K^{-1})**	**WWR (%)**	**Lighting Control Strategy**	**ΔPED_H (%)**	**ΔPED_C (%)**	**ΔPED_L (%)**	**ΔPED_T (%)**
0.79	2.89	25	automatic on/off	base case	base case	base case	base case
0.57	1.40	77	automatic on/off	−8	−21	−13	−11
			dimming	−2	−26	−48	−13
	1.10	77	automatic on/off	−12	−19	−13	−13
			dimming	−6	−24	−48	−16
0.46	1.40	77	automatic on/off	1	−35	−12	−6
			dimming	7	−39	−47	−9
	1.10	77	automatic on/off	−3	−34	−12	−9
			dimming	3	−38	−47	−11
	0.70	77	automatic on/off	−9	−32	−11	−13
			dimming	−3	−37	−47	−15
0.40	1.40	77	automatic on/off	6	−41	−11	−3
			dimming	12	−46	−47	−6
	1.10	77	automatic on/off	2	−41	−11	−6
			dimming	8	−45	−47	−9
	0.70	77	automatic on/off	−5	−38	−11	−10
			dimming	1	−42	−47	−13

The comparison of the achievable percentage savings shows that heating primary energy demand is characterized by the lowest decrease, with potential savings ranging from about 8% for Milan, 6% for Bologna, 7% for Rome and 4% for Naples (Tables 7–10 and Figure 3).

Maximum savings on lighting and cooling primary energy needs were obtained with a dimmable lighting control strategy dependent on daylight illuminance, rather than an automatic on/off switch. Indeed, the former allows one to save nearly 40% more energy than the latter. Furthermore, savings on lighting primary energy demand were generally more significant than those on cooling, as illustrated in Figures 4 and 5. Indeed, the former range from 47%, for the cities of Rome and Naples, to 50% for Milan and Bologna, while the latter were equal to about 37% (Tables 7–10).

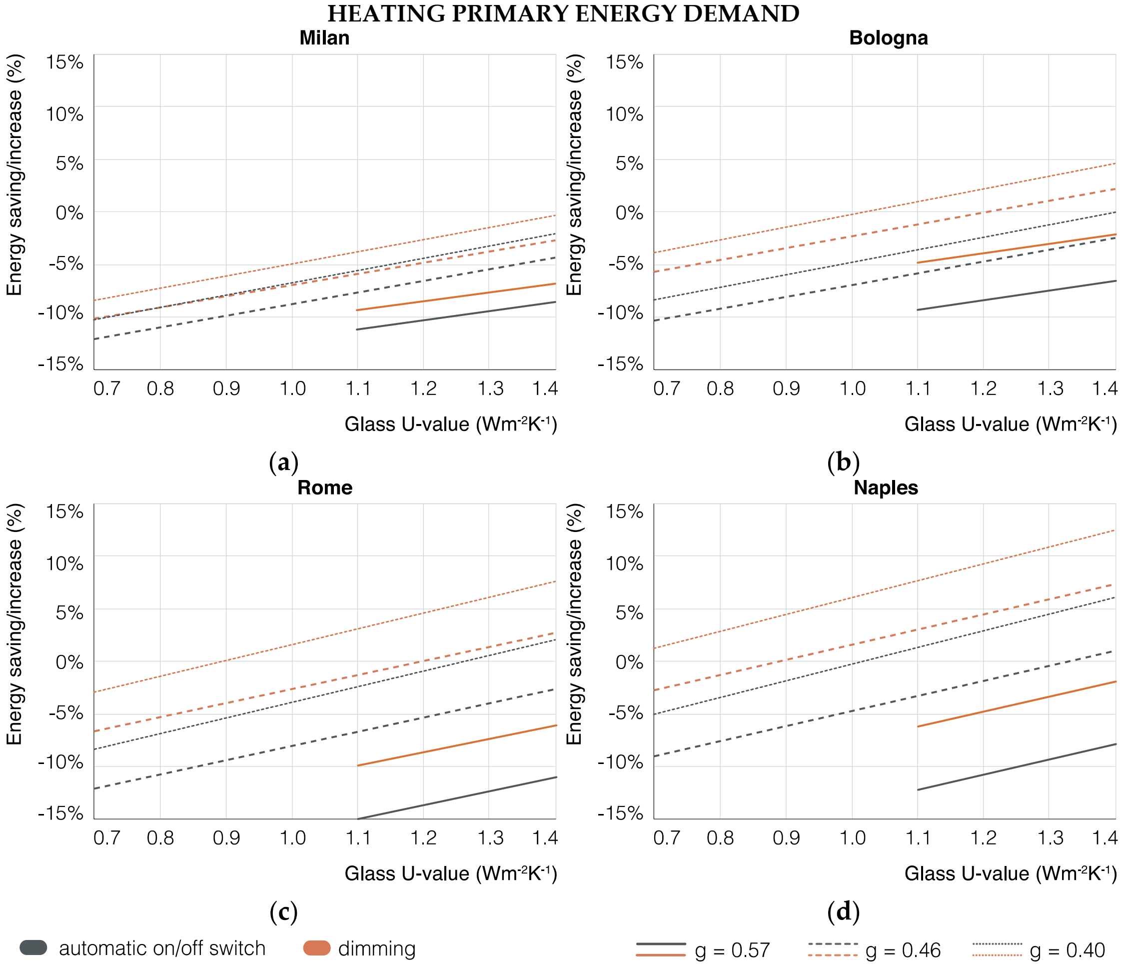


Figure 3. Percentage reduction or increase in heating primary energy demand compared to the west-facing base case by adopting the 77% WWR window in relation to the U-value, g-value and lighting control strategy.

Nevertheless, for a proper understanding of the results obtained it is necessary to analyze the data in view of the breakdown of primary energy demand by end-use. As mentioned before, primary energy needs for heating represent about 82% of the total room primary energy demand, followed by lighting (11%) and cooling (7%). Therefore, when considering potential reductions in energy expressed in absolute values, heating energy savings are generally higher or almost equal to the savings achievable on cooling primary energy demand for the cities with higher heating degree days (HDD; Milan and Bologna). In regards to the lighting, it was found to be the end use on which the highest savings could be obtained also when analyzing the results expressed in absolute values (Appendix A).

Considering the balance between heating, cooling and lighting energy savings, the most advantageous glazing solutions are those characterized by a g-value of 0.40 and 0.46 and a U-value of 0.70 $Wm^{-2}K^{-1}$ for the cities of Milan and Bologna, and the glazing type with a g-value of 0.57 and a U-value of 1.10 $Wm^{-2}K^{-1}$ for the cities of Rome and Naples, for which the second glazing solution is the best as well.

The most significant savings on cooling primary energy needs may be achieved with the glazing type characterized by a g-value of 0.40 and a U-value of 1.40 $Wm^{-2}K^{-1}$, when a daylight-linked dimming control was adopted, as illustrated in Figure 4. This glazing solution allows us to reduce cooling primary energy demand by up to 47% for Rome (Table 9), 46% for Naples (Table 10) and 45% for the cities of Milan (Table 7) and Bologna (Table 8).

COOLING PRIMARY ENERGY DEMAND

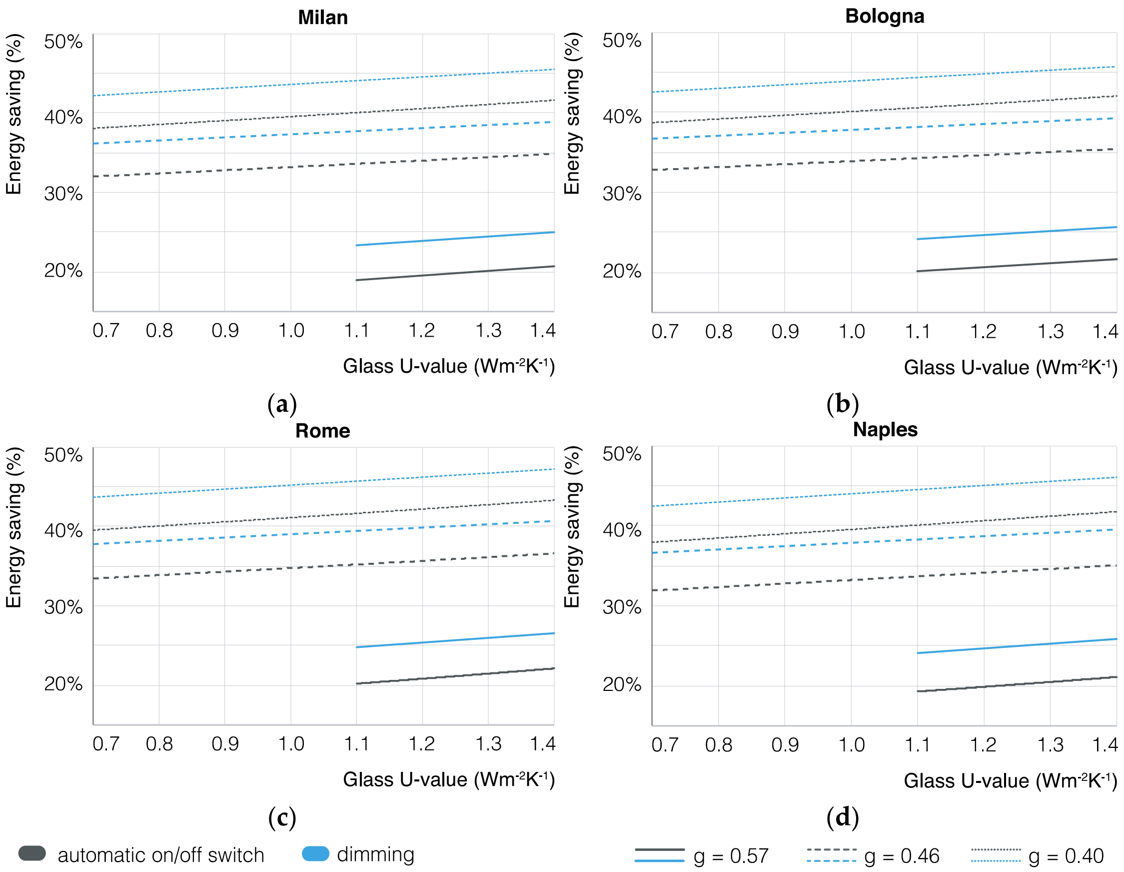


Figure 4. Achievable savings on cooling primary energy demand of the west-facing base case by adopting the 77% WWR window in relation to its U-value, g-value and lighting control strategy.

Nevertheless, this glazing type brings to the lowest savings or highest increase in heating primary energy needs too, equal to a 1% reduction for Milan (Table 7) and a rise of 4% for Bologna (Table 8), 8% for Rome (Table 9) and 12% for Naples (Table 10).

Indeed, appropriate values of glazing specifications to reduce primary energy needs for heating are opposite to those necessary to maximize savings on cooling primary energy demand (Figures 3 and 4).

Considering the lighting primary energy demand, Figure 5 outlines that all the glazing types considered allowed us to achieve nearly the same energy savings, being characterized by more or less the same value of visible transmittance (Tvis). The highest savings on primary energy needs for lighting may be obtained in Bologna and Milan, with a reduction of 50% when adopting a daylight-linked dimming control.

4. Conclusions and Future Developments

The adoption of wider openings with appropriate glazing specifications can dramatically lower energy needs and the related costs in hospital patient rooms, while improving patient and staff well-being, which benefits from the increased exposure to daylight and to an outside open sky view.

The present study assessed and compared the effects of several window dimensions and glazing properties on the primary energy demand for heating, cooling and lighting of a hospital patient room under four orientations and four climatic conditions using dynamic building energy simulations. More in detail, the performance of a base case window with 25%WWR, thermal transmittance of 2.89 $Wm^{-2}K^{-1}$ and g-value of 0.79 was compared to a 77% WWR window under nine glazing systems with different U-values and g-values and considering four orientations and four climatic conditions—Milan, Bologna, Rome and Naples.

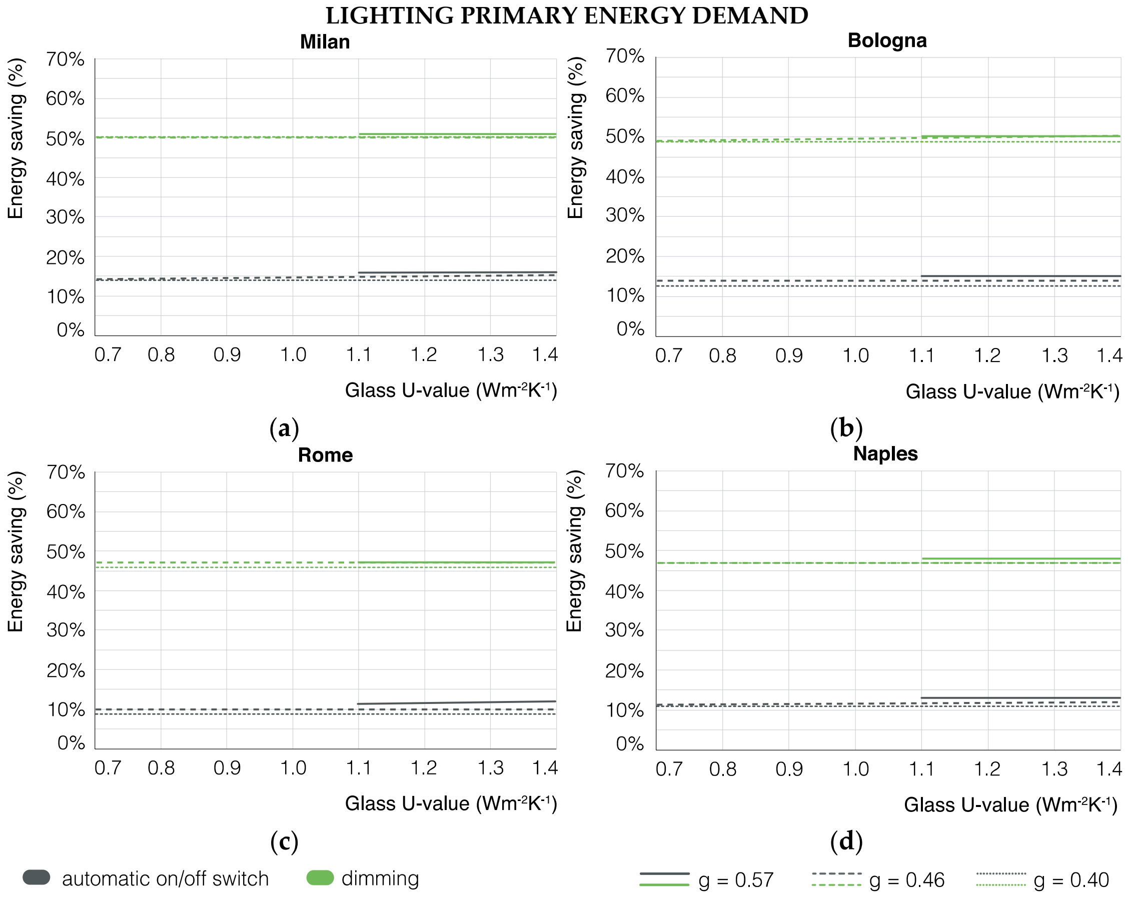


Figure 5. Achievable savings on lighting primary energy demand of the west-facing base case by adopting the 77% WWR window in relation to its U-value, g-value and lighting control strategy.

Furthermore, two lighting control systems were analyzed, an automatic on/off switch and a dimmable lighting control strategy dependent on natural light illuminance, in order to take full advantage of the positive effects of wider windows and, more in detail, of their contribution in maximizing energy savings.

Results reported above showed that appropriate glazing specifications to achieve the highest heating energy savings were opposite to those necessary to reduce the primary energy demand for cooling. The glazing solution with a g-value of 0.40 and a U-value of 1.40 $Wm^{-2}K^{-1}$ allowed us to obtain the best savings on cooling primary energy needs (up to 47%), but it brought the highest increase in heating primary energy demand too. This is due to the fact that heating loads can be reduced by adopting glazings with low U-values for low heat losses and high g-values to increase solar gains. However, these characteristics are not energy-efficient during the cooling period. This finding underlines the need to separately consider heating and cooling primary energy needs when selecting the best glazing solution. More in detail, for each location it is necessary to analyze the weather data in order to identify the end use that contributes the most to the overall primary energy demand.

Taking into consideration heating, cooling and lighting primary energy needs individually, the highest energy savings could be achieved on the lighting primary energy demand, which could be reduced up to 50% when a daylight responsive dimming control is adopted. Slightly lower savings, approximately equal to 37%, could be reached on primary energy needs for cooling, while the lowest percentage reductions were achieved on the heating primary energy demand, varying from about 8% to 4%. Although, being heating the most responsible end use for total primary energy needs, when considering results expressed in absolute values the savings achievable on heating were higher or nearly equal to those on cooling for the cities with higher heating degree days (HDD; Milan and

Bologna). Despite this, lighting was found to be the end use on which the maximum savings could be reached also when considering results expressed in absolute values (Appendix A).

In regards to the balance between the energy savings achievable on heating, cooling and lighting primary energy needs, the most advantageous glazing solution was the one with a g-value of 0.40 and 0.46 and a U-value of 0.70 $Wm^{-2}K^{-1}$ for the cities with higher heating degree days (HDD) (Milan and Bologna), and with a g-value of 0.57 and a U-value of 1.10 $Wm^{-2}K^{-1}$ for the cities with lower heating degree days (Rome and Naples).

For a more comprehensive interpretation of the findings obtained it is necessary to underline that optimizing the type of glazing and lighting control strategy in hospital patient rooms did not only allow us to reduce energy consumption and cut energy-related costs. As outlined in Table 11, for each kWh of electricity or natural gas, 0.45 and 0.20 kg carbon dioxide emissions ($kgCO_2$) were released respectively.

Table 11. Carbon dioxide emission conversion factors [108,111–114].

Fuel	$kgCO_2$ per kWh
Electricity	0.45
Gas	0.20

Therefore, taking into account the glazing solutions that allow us to achieve the maximum energy savings on all the end uses, it was found that those characterized by a g-value of 0.46 and a U-value of 0.70 $Wm^{-2}K^{-1}$, for the cities of Milan and Bologna, and the glazing types with a g-value of 0.57 and a U-value of 1.10 $Wm^{-2}K^{-1}$, for the cities of Rome and Naples, enabled to cut the related carbon emissions in a range between 111 and 205 $kgCO_2$ per year, equal to 14%–17% (Table 12). Considered that health carbon footprint represents about 5% of the national carbon footprint in OECD countries—10% in the U.S., 7% in Australia and 5% in Italy [115]—the application of measures aimed at reducing carbon emissions results to be of the utmost urgency.

Table 12. Reduction in carbon emissions.

City	Primary Energy Savings (kWh)	Reduction in Carbon Emissions	
		($kgCO_2$)	(%)
Milan	1010	205	16
Bologna	719	147	14
Rome	655	134	17
Naples	542	111	16

Savings achievable on the primary energy demand for heating may be maximized by activating the shading systems during the night in order to further reduce thermal losses. This issue will be properly investigated in the next research steps. In addition, a cost-optimal analysis of the solutions analyzed will be conducted with the aim of developing a robust decision-making tool that could support professionals when designing measures for a building energy refurbishment. Among the future developments of the study will be the analysis of (i) the dynamic primary energy calculation considering in the simulation the time depending efficiency of the electric energy provided by the grid and (ii) the carbon dioxide emissions taking into account its time depending factor.

Author Contributions: S.C. contributed to the definition of the model, the simulations' conditions and carried out the simulations. P.V. and M.C. designed and implemented the simulation tools, S.M. gave the direct supervision for the research. All authors discussed and provided comments at all stages. All authors have read and agreed to the published version of the manuscript.

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Conflicts of Interest: The authors declare no conflict of interest.

Appendix A

This appendix illustrates the primary energy demand (PED) for heating, cooling and lighting of the patient room evaluated for each glazing type and lighting control strategy for the four cities considered, Milan, Bologna, Rome and Naples. The findings were used to identify the percentage change in primary energy demand and the achievable energy savings presented in Tables 7–10 and in Figures 3–5.

Table A1. Primary energy demand for heating, cooling and lighting evaluated for each glazing type and lighting control strategy in Milan.

Milan							
g-Value (Dimensionless)	**U-Value (Wm^{-2}K^{-1})**	**WWR (%)**	**Lighting Control Strategy**	PED_H **(kWh)**	PED_C **(kWh)**	PED_L **(kWh)**	PED_T **(kWh)**
0.79	2.89	25	automatic on/off	5221	408	663	6292
0.57	1.40	77	automatic on/off	4775	323	557	5655
			dimming	4868	306	324	5498
	1.10	77	automatic on/off	4638	330	560	5528
			dimming	4737	312	326	5375
0.46	1.40	77	automatic on/off	4984	266	565	5816
			dimming	5079	249	329	5657
	1.10	77	automatic on/off	4828	270	566	5664
			dimming	4922	253	330	5505
	0.70	77	automatic on/off	4586	277	568	5431
			dimming	4691	260	330	5282
0.40	1.40	77	automatic on/off	5101	239	570	5911
			dimming	5193	223	332	5749
	1.10	77	automatic on/off	4948	242	572	5762
			dimming	5036	226	333	5595
	0.70	77	automatic on/off	4681	253	572	5506
			dimming	4777	237	333	5346

Table A2. Primary energy demand for heating, cooling and lighting evaluated for each glazing type and lighting control strategy in Bologna.

Bologna							
g-Value (Dimensionless)	**U-Value (Wm^{-2}K^{-1})**	**WWR (%)**	**Lighting Control Strategy**	PED_H **(kWh)**	PED_C **(kWh)**	PED_L **(kWh)**	PED_T **(kWh)**
0.79	2.89	25	automatic on/off	4189	421	663	5272
0.57	1.40	77	automatic on/off	3917	330	562	4808
			dimming	4101	313	329	4,743
	1.10	77	automatic on/off	3800	336	564	4701
			dimming	3988	319	330	4638
0.46	1.40	77	automatic on/off	4086	272	570	4928
			dimming	4279	256	334	4869
	1.10	77	automatic on/off	3954	276	571	4801
			dimming	4145	260	334	4739
	0.70	77	automatic on/off	3756	283	572	4612
			dimming	3952	267	335	4554
0.40	1.40	77	automatic on/off	4180	245	575	5001
			dimming	4375	230	337	4941
	1.10	77	automatic on/off	4052	248	576	4877
			dimming	4241	232	337	4810
	0.70	77	automatic on/off	3835	259	576	4670
			dimming	4024	243	337	4604

Table A3. Primary energy demand for heating, cooling and lighting evaluated for each glazing type and lighting control strategy in Rome.

Rome							
g-Value (Dimensionless)	**U-Value ($\text{Wm}^{-2}\text{K}^{-1}$)**	**WWR (%)**	**Lighting Control Strategy**	PED_H **(kWh)**	PED_C **(kWh)**	PED_L **(kWh)**	PED_T **(kWh)**
0.79	2.89	25	automatic on/off	2787	411	586	3784
0.57	1.40	77	automatic on/off	2477	320	518	3315
			dimming	2620	302	306	3228
	1.10	77	automatic on/off	2366	328	521	3215
			dimming	2512	309	307	3129
0.46	1.40	77	automatic on/off	2715	261	526	3502
			dimming	2866	244	310	3421
	1.10	77	automatic on/off	2603	266	527	3396
			dimming	2753	248	311	3312
	0.70	77	automatic on/off	2451	274	528	3253
			dimming	2603	256	312	3171
0.40	1.40	77	automatic on/off	2843	234	531	3608
			dimming	2997	218	313	3528
	1.10	77	automatic on/off	2733	238	532	3503
			dimming	2884	221	314	3419
	0.70	77	automatic on/off	2553	249	532	3334
			dimming	2704	232	314	3250

Table A4. Primary energy demand for heating, cooling and lighting evaluated for each glazing type and lighting control strategy in Naples.

Naples							
g-Value (Dimensionless)	**U-Value ($\text{Wm}^{-2}\text{K}^{-1}$)**	**WWR (%)**	**Lighting Control Strategy**	PED_H **(kWh)**	PED_C **(kWh)**	PED_L **(kWh)**	PED_T **(kWh)**
0.79	2.89	25	automatic on/off	2351	457	599	3406
0.57	1.40	77	automatic on/off	2166	360	520	3047
			dimming	2306	339	310	2955
	1.10	77	automatic on/off	2064	369	523	2956
			dimming	2206	347	312	2864
0.46	1.40	77	automatic on/off	2375	297	528	3200
			dimming	2525	276	315	3116
	1.10	77	automatic on/off	2276	302	529	3107
			dimming	2423	281	316	3020
	0.70	77	automatic on/off	2139	311	530	2980
			dimming	2288	290	316	2895
0.40	1.40	77	automatic on/off	2489	267	533	3289
			dimming	2641	248	318	3207
	1.10	77	automatic on/off	2390	271	534	3196
			dimming	2540	251	319	3110
	0.70	77	automatic on/off	2231	284	534	3049
			dimming	2379	264	319	2962

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