

Glazing's techno-economic performance: A comparison of window features in office buildings in different climates

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Abstract

The use of glass in buildings has a considerable impact both on comfort levels and energy performances, since glazed components protect from external environmental conditions, provides daylighting, view and also ventilation if they are openable. Starting from the second half of the 19th century, the architectural design used to give an increasingly important role to the glass, particularly in non-residential buildings, almost in every kind of climatic conditions. In this context, the present work aims to assess the techno-economic performance of glazing with various thermophysical and optical properties and different glass/wall ratios, coupled with internal/external shading systems, considering the application on an office building in 3 different representative European climates. The obtained results demonstrate that there is a negative impact of solar gains on the yearly energy balance of modern office buildings, where thermally-insulated envelopes enhance overheating even in cold climates. Because of this, the most reasonable solution to decrease the yearly energy consumption is to limit the amount of glazing or to use external solar shading devices. It can be also stated that, under a global-cost perspective, the best cost-effectiveness is achieved using a solar control glazing without any shading. If, however, the cost of discomfort due to glare is accounted, the use of solar shading devices emerges as the most convenient option in all analysed cases.

Keywords: Glazing, Solar shading, Energy savings, Office buildings, Overall cost analysis

1. Introduction

The buildings sector is responsible for about 33% of the World's final energy consumption [1] (second only to the industry sector) and for the largest share at EU level – about 40% – with an equivalent impact on greenhouse gas emissions [2]. Of this, a significant fraction is attributable to commercial buildings, being their energy needs for heating, cooling and lighting much higher compared to those of residential buildings [3]. Indeed, the office buildings' design is often more oriented to meet aesthetic requirements rather than functional ones, scarcely considering that the design process involves choices that have a great impact on energy consumption and on comfort. In particular, it is commonly believed that a great amount of glazing surfaces makes buildings more fashionable and comfortable. Whereas there is no doubt that glass envelopes are light and transparent architectural components, windows should be regarded as fundamental elements in the control of internal space quality, in virtue of their very important role in determining the level of both thermal and visual comfort [4,5]. Although occupy-

ing only a fraction of the façade, transparent elements have a crucial impact on the building's overall performance as they modulate the interaction with the external environment acting as a filter against environmental conditions (solar radiation, external temperatures, wind, noise, etc.) and providing daylighting, ventilation and view. However, such functions are often conflicting since, for example, the need to shield the solar radiation could negatively influence the daylighting. In parallel, windows have a substantial influence on the total heating and cooling demand.

The recent interest on such topic is proved by the increasing number of research concerning the impact of glass surfaces in buildings [6–21]. Most of them concern the residential sector [6–8,15,16,18], which however has different features and peculiarities compared to the tertiary sector. Although some studies about office buildings were carried out, they are generally focused on the heating and cooling performance [21] without considering the artificial lighting consumption and the visual comfort of users, or analysing merely the daylighting illuminance level on the workplan [14]. Some research works analyse both thermal and visual comfort of windows coupled with different shading devices [11,13,17,20]. However, none of them take into account the economic issues related to investment, operation and maintenance costs of windows as well as shading systems. Even if in a few studies [10,12]

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Nomenclature

g	Solar transmittance of the glazing or solar heat gain coefficient [-]
U	Thermal transmittance [W/m^2K]
S_w	Window's surface [m^2]
WWR	Window to wall ratio [%]
τ_v	Visible transmittance of the glass [-]
τ_v/g -value	Glass selectivity index [-]
ρ	Reflection coefficient [-]
ε	Emission coefficient [-]
ACH	Air changes per hour [vol/h]
C_i	Initial investment cost needed to purchase and install the window, the opaque wall and, if present, the shading system [€]
$C_{a,i}$	Annual running cost during each year i , which is the cost of the energy needed for heating, cooling and artificial lighting and the maintenance cost, if present [€]
t	Length of the calculation period [years]
r	Real interest rate [-]
$V_{f,t}$	Residual value of the components at the end of the calculation period [€]
SPF_{HVAC}	Average seasonal performance factor of the HVAC system [-]
DGI	Discomfort glare index [-]

the cost optimality of different glazed solutions applied to office buildings is assessed, it is related just to heating performances. Finally, none of the above mentioned works takes into account all the affecting parameters, such as the type of glasses, the Window to Wall Ratio, solar control strategies and climates, which can impact on the building's overall performance.

In such respect, the present work aims to analyse in detail the influence of glazed surfaces on the energy performance of office buildings and to quantify the impact on the final energy demand, on the global cost, on the GHG emissions and on the comfort level. For such purpose, we make use of computer simulations on a virtual reference room. Our study evaluates different types of fenestration products with various thermophysical and optical properties (combinations of thermal transmittance, solar transmittance and visible transmittance) and configurations (different glass/wall ratio), coupled with internal/external shading systems and in 3 different representative European climates.

Finally, our study allows, in each climatic context, to provide engineers and architects with a set of simplified tips to identify: (i) the windows' proprieties that mostly affect energy consumption in office buildings, (ii) the most suitable solar shading devices for maximizing overall energy saving and (iii) the best solutions in terms of global cost.

2. Methodology and model set-up

In the study here presented we assess and compare the performances of different windows and solar shading solutions applied to a computer-modelled reference room of an office building under energy (heating, cooling, lighting) and economic (global cost, GHG emission cost, cost of discomfort) points of view. The visual comfort level in terms of glare control is also evaluated.

Thermal energy demand (heating and cooling) and lighting demand are simulated using Energy Plus, a worldwide known software for accurate energy simulations [22,23]. More in detail, the assessment is carried out on a set of windows characterized by different features (glazed surface, thermal/optical parameters, type of

shading system), as described in detail in Section 2.4 and considering 3 reference application contexts (Athens, Milan and Stockholm) representing warm Mediterranean, warm continental and cool continental climates [24]. A total number of 144 scenarios are reported below.

For each scenario, the total yearly energy demand for heating, cooling and artificial lighting has been evaluated, considering – for all cases – the same configuration of the technical systems (i.e. heat generation, distribution and emission subsystems and lighting system). Subsequently, we carried out for each analysed configuration an economic evaluation based on the results obtained from the energy simulation using the *global cost calculation method* [25].

2.1. The reference room

Energy analysis was performed considering a virtual reference room (Fig. 1) with a geometry defined according to the EN 15265:2007 standard [26]. The reference room has a rectangular plan, 3.6 m wide and 5.5 m long, with a net storey height of 2.8 m. According to the EN 12464-1 [27], the evaluations related to lighting issues were carried out considering a work plane placed 85 cm above the floor (typical height of an office desk); for simulation purposes such surface is divided in a calculation grid composed by 80 cells, in order to estimate the illuminance level in each unit cell. In addition, the reference room has a glazed surface on one of the two smaller vertical sides, assumed to face outdoor and oriented towards South. This configuration has been chosen to represent an office space inside a tertiary building.

All opaque building components of the reference room were considered adiabatic, since they are supposed to be facing other internal environments, except for the South wall containing the window. The U of this wall was set equal to $0.30 W/m^2K$, a typical value imposed by the European building regulations in recent years [28]. An external finishing made with plaster with a solar absorptance of 0.3 was also supposed.

In order to reach this result, we set as initial condition a common solution realized with internal plaster, hollow bricks, insulation material and external plaster. The slabs are covered with tiles and the internal walls realized with plasterboard as the simple office division. The average thermal capacity of the opaque components is approximately equal to $70 kJ/m^2K$.

We would like to stress that the present research follows an approach already used and verified in several other published works [29–32]. In detail, the before-described virtual model of the room has been calibrated and validated using actual measurements carried out both on a real office room and on a scale-model of the same environment, thus confirming the consistency and the reliability of the obtainable results in terms of energy and lighting performances.

2.2. Load profiles

In order to consider a typical office load profile, we assume the reference room to be occupied during the week, from 08:00 to 20:00 every day, all year long. Such a full occupation condition has been defined to generalize and simplify the whole assessment. In this way, general evaluations are not affected by the fluctuations in occupancy profiles.

The heating and cooling set-points were considered respectively equal to $20^\circ C$ and $26^\circ C$ during the whole year. Although these values may differ from the ones found in specific national standards, they are compliant with EN 15251 [33], to take in consideration the European specifications. Internal loads, excluding artificial lights, are set equal to $10 W/m^2$ during occupation time and to $2 W/m^2$ for the remaining time. Infiltration and ventilation are considered equal to 0.85 Air Changes per Hour (ACH), with heat recovery of

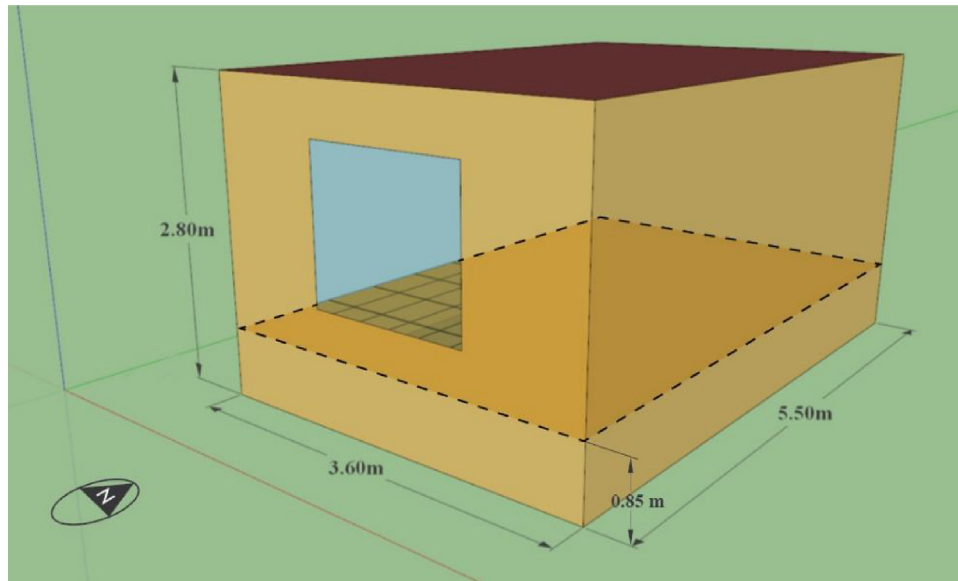


Fig. 1. View of the reference room.

Table 1
Geographic and climatic data at case study locations in Europe [39].

	Athens	Milan	Stockholm
Altitude above sea level [m]	15	103	61
Latitude [°]	N 37.90	N 45.42	N 59.65
Longitude [°]	E 23.72	E 9.27	E 17.95
HDD (Heating Degree Day)	1210	2689	3581
CDD (Cooling Degree Day)	2519	1773	1232
Yearly average temperature [°C]	18.6	11.7	6.6
Horizontal Irradiation [kWh/m ² y]	1'582	1'244	977

50%, during the operating time and to 0.15 ACH for the remaining time. The lighting power density is evaluated according to the simplified design method of *total flux* [34], assuming dimmerable LED lamps with an efficiency of 120lm/W [35–37] and reflectance of the ceiling, walls and floor respectively equal to 0.7, 0.5 and 0.2. Therefore, in order to provide 500 lx on the two sensors, displaced according to Fig. 3, and a minimum illuminance of 300 lx on the whole calculation grid, the peak lighting power density has been set equal to 10 W/m² during the operating time.

2.3. Reference climatic contexts

In order to provide results that can be considered representative in several climatic contexts, we specified our study for three reference cities: Athens, Milan and Stockholm – which well represent the characteristics of the main European climates cited above. In detail, Athens is considered representative of Southern Europe [38], Milan of Central Europe and Stockholm of Northern Europe. In Table 1, we report the main climatic data of the reference locations.

2.4. Configurations of the glazed surfaces

In the present analysis, the window of the room has a variable surface (S_w) that ranges from 20% to 80% of the façade area (10 m²), according to four Window to Wall Ratios (WWR), respectively equal to 20%, 40%, 60% and 80%, as show in Fig. 2.

Moreover, we consider different thermal and optical features of windows referred to advanced market windows components: U varies in the range 1.5 W/m²K–0.7 W/m²K, the g factor in the range 0.72–0.43 and glass visible transmittance (τ_v) in 0.80–0.71.

Table 2
Thermal and optical properties of the examined glazing systems.

Window	U	g	τ_v	τ_v/g
	[W/m ² K]	[-]	[-]	[-]
A (standard double glazing)	1.5	0.72	0.75	1.04
B (high-performance double glazing)	1.1	0.61	0.80	1.31
C (high-performance double glazing, solar control)	1.1	0.43	0.71	1.65
D (triple glazing, solar control)	0.7	0.50	0.71	1.42

In particular, we identify four reference configurations according to the features summarized in the following table.

It must be noted that, in order to simplify the evaluation, the thermal transmittance (U) in Table 2 is the value related to the whole window, i.e. comprehensive of both glass and frame.

Finally, we consider also two kinds of shading systems applied to the windows relating them to reference market products:

- an internal roller curtain with a semi-transparent texture (with a solar transmittance equal to 0.4) placed at a distance of 5 cm from the glass;
- an external shading system consisting in moveable aluminium venetian blinds (ρ equal to 0.7 and ε equal to 0.1) with slat width of 7.3 cm and with a distance among slats of 7 cm, placed at a distance of 5 cm from the glass.

We assume both shading systems to be equipped with electric motors and an automated control system. The latter activates the shading when the incident solar radiation exceeds a specific irradiance level, as defined in Table 4, or when the discomfort glare index (DGI) on at least one of two users of the reference room (one facing the east opaque wall and the other facing the west opaque wall, as shown in Fig. 3) is higher than 28. Although the DGI presents some limits related to the differences in human perception of glare, it can be considered the main index for the evaluation of daylight discomfort glare, for sources with non-uniform levels of luminance [40].

The adopted DGI threshold, defined by the EN 12464-1, is the value above which the glare sensation becomes unbearable [27]. Such value can be considered reasonable since users may freely adjust their position and view in order to minimize the effect of glare, according to a so-called adaptive zone [41].

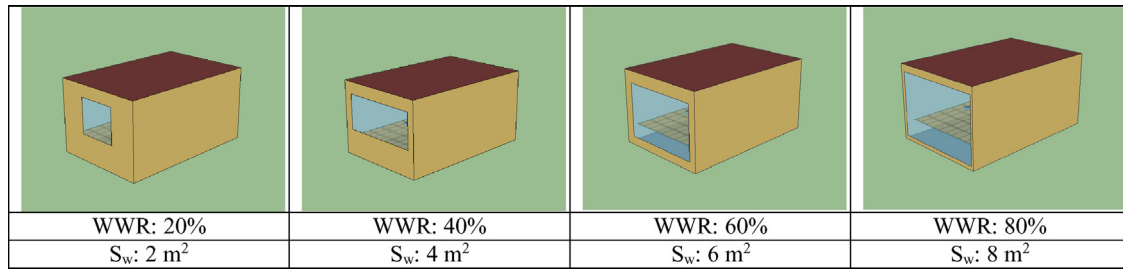


Fig. 2. Reference room with the four different sizes of the glazed surface.

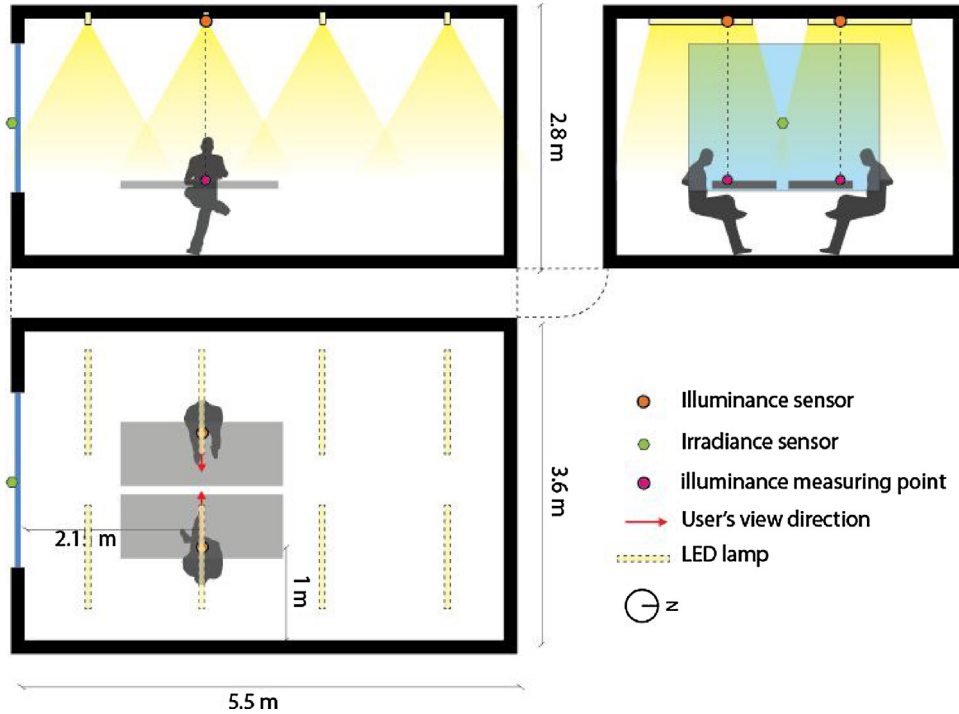


Fig. 3. Sensors and users position.

Table 3
Periods during which the solar irradiance control on the shading system is used.

Location	WWR			
	20%	40%	60%	80%
	From/to			
Athens	01 Jan/31 Dec	01 Jan/31 Dec	01 Jan/31 Dec	01 Jan/31 Dec
Milan	15 Apr/15 Oct	15 Feb/15 Nov	15 Feb/15 Nov	15 Feb/15 Nov
Stockholm	15 May/30 Sep	15 Mar/31 Oct	15 Mar/31 Oct	15 Mar/31 Oct

Table 4
Level of irradiance [W/m^2] on the vertical surfaces at which the shading system is used.

Window	WWR			
	20%	40%	60%	80%
A	300	150	100	100
B	300	150	100	100
C	300	200	150	100
D	300	200	150	100

In order to maximize solar gains only when needed, the control related to solar irradiation is used only during certain periods, defined for each climatic context as specified in Table 3. Thus, outside these periods, the shadings are used just when the glare index exceeds the supposed threshold, otherwise they remain

packed/rolled up. The selection of different periods for each location and WWR was made considering the days during which, in free floating conditions, the internal room temperature exceeds 26°C and thus the use of a solar irradiance control has a positive effect on the cooling energy demand. Glare control is set throughout the whole year since we assume that the shading system avoids glare even when the irradiance is below the threshold or the irradiance control is not active.

The irradiance threshold was defined identifying, for each configuration, the value at which it is possible to obtain the minimum overall yearly demand of heating, cooling and artificial lighting. The calculated values are reported in Table 4.

When the internal curtain is activated it is supposed to remain completely unrolled. Otherwise the external blinds when activated are unpacked with a variable tilt angle, in order to completely block the beam solar radiation incident on the window surface.

To sum up, the simulations were performed with 48 different configurations for each of the three reference locations. The different options were thus defined according to the following parameters:

- 4 types of glasses: A, B, C, D (See Table 2);
- 4 WWR: 20%, 40%, 60%, 80% (See Fig. 2);
- 3 solar control strategies: no shading (NS); internal curtain (IC); external shading (ES).

3. Energy analysis

In the next paragraphs, we report our results in terms of thermal energy losses/gains through the window surface and artificial lighting thermal load. The energy rate through the windows is divided in “positive” fluxes (i.e. those that allow the reduction of energy consumption) and “negative” fluxes (i.e. those which increase the energy consumption). During winter, gains are considered positive while thermal losses negative. On the contrary, during summer positive flows are thermal losses and negative flows are gains. The thermal influence of artificial lighting is represented in terms of net contribution, which is the difference between the positive gain during winter and the negative load during summer. The remaining internal thermal gains (e.g. electric appliances, persons) were not represented in the following graphs since they are not related to the amount of glazing nor the presence of shadings.

Subsequently, the energy consumptions for heating, cooling and artificial lighting are also reported in terms of final electric energy demand. In particular, the electricity needed for heating and cooling is calculated assuming in all cases the same technical system: an electric vapour-compression water–water heat pump coupled with fan-coils. At present, the chosen system can be considered the best available technology on the market for heating and cooling in an office building and its performance is not affected by climatic conditions (e.g. the ambient air temperature), thus it can be successfully used to compare the 3 cases. In detail, we assumed an average seasonal global performance factor of the HVAC system (SPF_{HVAC}), which is ratio between the useful thermal energy emitted in the thermal zone and the electricity needed to run the entire HVAC plant, equal to 3, both for heating and cooling purposes. In fact, although the mean ground temperature in the 3 selected locations hasn't exactly the same yearly average value [42], the resulting incidence on the overall performance of the entire HVAC system all around the year (heating and cooling) was considered negligible for the scope of the present work. More in detail, the chosen SPF_{HVAC} value is based on the real performances of common heat pumps [43–45] and includes the efficiencies of the various subsystems (distribution, control and emission), together with the auxiliary electric consumption (e.g. circulation pumps, fans, etc.). The latter, in fact, significantly affect the overall energy balance of energy-efficient buildings, regardless the climatic context [46]. Therefore, SPF_{HVAC} must be considered as a reference performance factor with the aim to compare different envelope solutions.

The control system of the artificial lighting, instead, was set in order to provide 500lx on the two sensors and an average illuminance over 300lx on the whole calculation grid (Fig. 3). The latter value can be considered the minimum illuminance level to ensure the visual comfort in offices [27]. The overhead lights dim continuously and linearly the power in order to provide the established illuminance level on the sensors considering the daylighting contribution, as schematically shown in Fig. 4.

The artificial lighting system was set to be strictly operated according to the occupancy of the room.

All data reported hereafter are expressed in quantities of annual thermal energy per unit of net floor area [kWh/m^2y] and of electric energy per unit of net floor area [kWh_e/m^2y].

3.1. Impact of window size and features

The first results assess the impact of different glazed surfaces and of their features on the overall energy performance, without considering the application of shading systems. Specifically, we are able to state that in hot climates, where energy consumption is mainly due to cooling, window's large size negatively affects the building's performance even in the presence of solar-control glass.

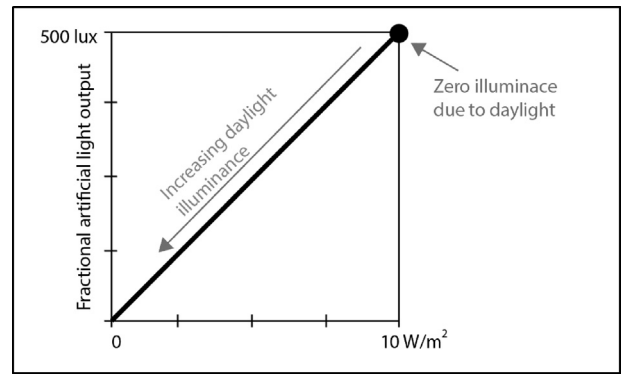


Fig. 4. Control logic of the continuous dimming system.

Table 5

Time exceeding maximum allowable glare index [hours].

Location	WWR			
	20%	40%	60%	80%
Athens	164	224	224	276
Milan	136	177	178	245
Stockholm	181	245	245	292

In Fig. 5 are firstly represented thermal fluxes related to gains (positive in winter and negative in summer) and losses (positive in summer and negative in winter) through the window, together with the net annual thermal contribution due to artificial lighting. In the second part of the figure, the final energy demand for each analysed configuration is represented in terms of specific electric consumption for heating, cooling and artificial lighting, taking into account all the elements of the building's energy balance and also the efficiencies of the technical systems.

As shown in the fluxes diagrams, although thermal losses do not greatly increase by increasing the WWR, solar gains greatly vary proportionally to the window size. Anyways, since solar gains are directly related to the optical properties of the glass, windows characterized by a low solar transmittance (such as Window C) perform better during the cooling season. Artificial lighting has a roughly constant thermal load, in each location and in all the analysed solutions. Thus, in the absence of shading systems, the only way to decrease solar gains is to apply a glass with a low g . However, in locations mainly characterized by low external temperatures, the application of such a glazing component slightly increases the energy consumption for heating.

Analysing final electricity consumption, the increase of the ratio between glazed and opaque surfaces negatively affects the building's final energy demand [29], especially in hot climates. More in detail, the overall electric energy consumption due to heating, cooling and lighting varies in the range of 26.9–85.9 kWh_e/m^2y in Athens, between 21.0 and 59.4 kWh_e/m^2y in Milan and between 25.1 to 61.7 kWh_e/m^2y in Stockholm.

Considering the overall energy consumption due to heating, cooling and artificial lighting, in the absence of shading devices Windows C can be considered the most suitable solution regardless of windows size and location.

Moreover, we conclude that for every kind of glass and in the three analysed climatic contexts, the overall consumption increases as the WWR increases. No advantages can be found under the energy point of view in increasing the amount of glass in an office building, which indeed leads to an increase in the time during which visual discomfort due glare occurs. In Table 5 the number of hours during which the glare threshold is exceeded is reported for each location and WWR.

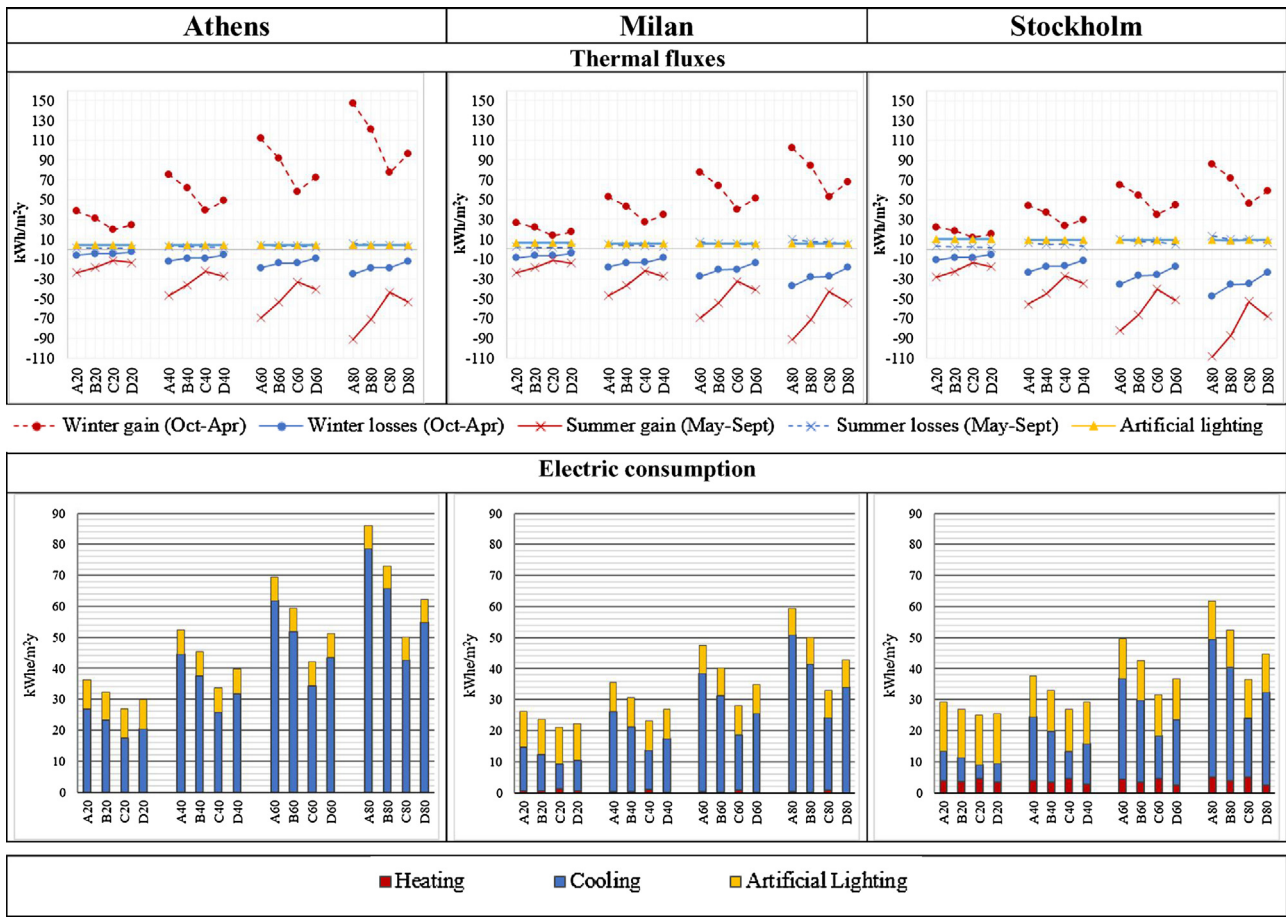


Fig. 5. Thermal fluxes and electric consumption without shading.

It must be noted that glare is typically identified as a major source of discomfort in working places [47], especially where personal computers are used [48].

3.2. Impact of windows shading systems

The use of shading systems is one of the most significant strategies for reducing cooling loads during summer and at the same time to avoid discomfort due to glare. This aim can be achieved by several means, such as movable or fixed shadings. In the present paper, we have considered 2 different shading systems, as described in Section 2.4.

As expected, our analysis of the collected results confirms a significant reduction of solar loads during the cooling season thanks to the shading systems. However, since the glare control is supposed to be set over the whole year, even during the heating season solar gains slightly decrease.

During the heating season, also the useful daylighting is marginally reduced due to glare control as well as during the cooling period, due both to glare and overheating control.

In any case, the increase of winter energy consumption due to the presence of shading devices is practically negligible compared to the summer energy saving, especially with a WWR equal or higher than 40%, as also stated by other studies [14,20,21].

Figs. 6 and 7 summarize the obtained results, firstly in terms of thermal fluxes and then of final electric consumptions, with the same logic described for Fig. 5.

Fig. 8 allows to compare the overall consumption related to the application of internal, external and no shading systems, for the three analysed locations. While the curtain placed in the internal

side limits minimally the total energy consumption during the year, external shading systems are the most suitable solutions considering WWR equal or higher than 40%. Moreover, the effectiveness of the external shading increases proportionally with the number of CDD.

As one can see, the application of a shading system always has a positive impact on overall energy consumption – even though benefit is limited for low WWR using solar control glazing. In detail, for WWR equal or higher than 40%, the solution that minimize the overall energy consumption is the solar control window with $t_v/g = 1.65$ (Window C) equipped with external shading. Such kind of glazing typically ensures the best performances regardless the use of shading systems, as also stated by other researchers [20]. For a WWR equal to 20%, instead, the application of the movable external shading on any type of window gives almost the same results as the unshaded solutions in terms of energy consumption, with a maximum decrease of 7%. This result is related to the small size of the window and thus to the limited amount of summer solar gains and of daylighting. In this case, the most suitable solution is the application of an internal curtain. This allows to partially control the solar gain in hot season without a significant reduction of daylighting (which is already limited by the relatively small size of the window) and ensures higher solar gain during winter.

We wish to stress that, even in heating-dominated climates, such as in Stockholm, the benefit of external shadings is considerable for WWR equal or higher than 60%, also in presence of a solar control glass. This is a common and widespread problem due to the huge negative impact of solar gains on the yearly energy balance of modern office buildings, where low U of the envelope limit heat losses and thus enhance the overheating problem also in cold

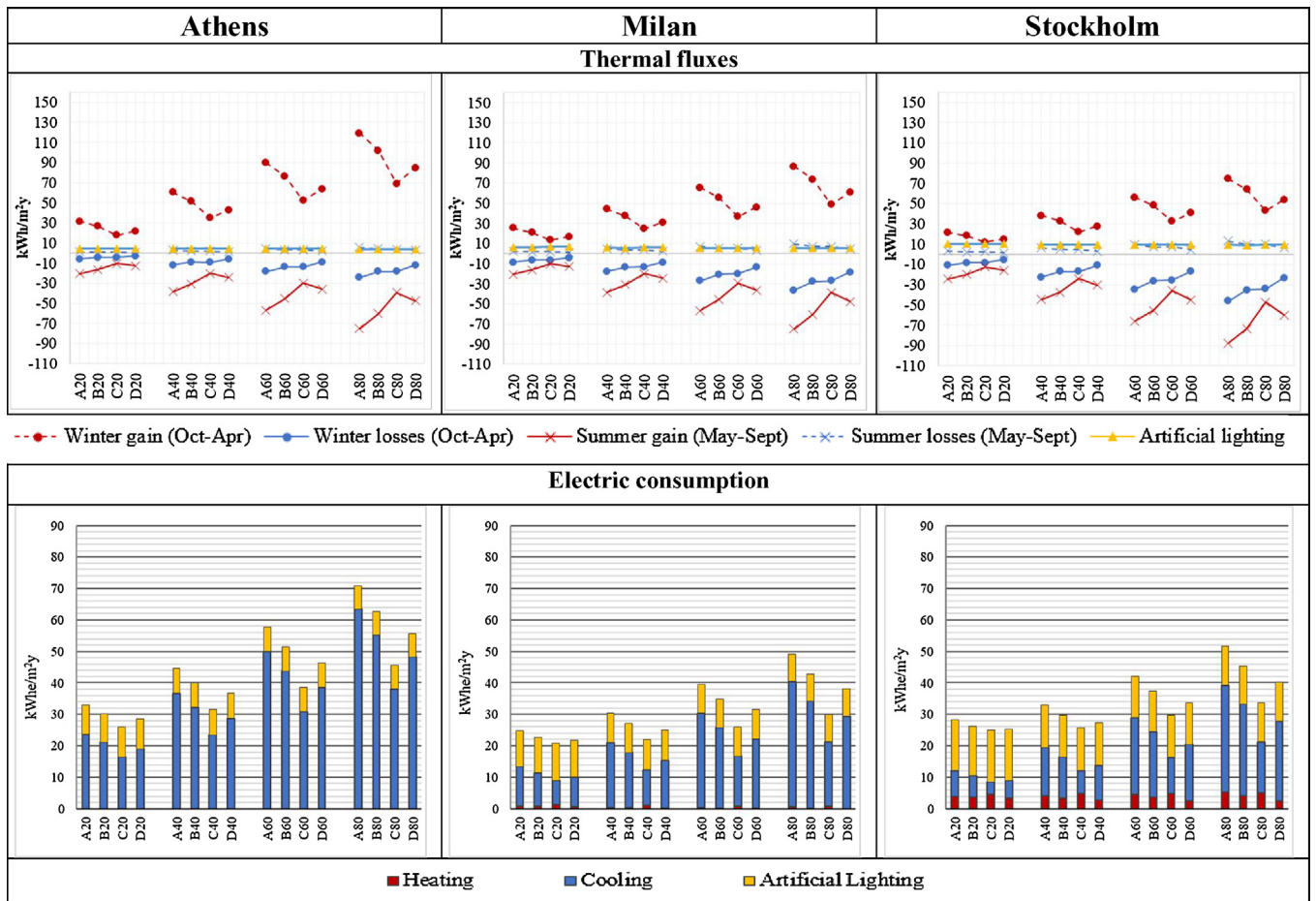


Fig. 6. Thermal fluxes and electric consumption with internal curtain.

climates. This statement is true also if the impact of artificial lighting on the whole energy consumption in Stockholm is considerable and slightly increased by the use of shadings.

Finally, it has to be noted that in all cases the use of shading devices totally avoids the discomfort due to glare, as reported in other works [11,17].

4. Economic analysis

The economic evaluation reported in this section, based on the results obtained from the energy analysis, was performed taking firstly into account the building investment and the running (energy and maintenance) costs. Secondly, a deeper analysis was performed considering also environmental costs due to emissions and productivity losses due to glare discomfort, as described in following sections.

4.1. Investment and running costs

In order to consider the investor/building owner's perspective, the global cost (C_G) during the reference lifetime was calculated for all the analysed options. In general, C_G accounts for the initial investment cost and the annual operation costs, considering the time value of money (standard present worth analysis) to construct the cumulative cash flow (year by year) and is calculated according to the following formula [49]:

$$C_G(t) = C_I + \sum_{i=1}^t \frac{C_{a,i}}{(1+r)^i} - V_{f,t}$$

Table 6

Investment cost of windows and shading systems.

Window/Shading	Investments cost [€/m ²]
Window A	290
Window B	305
Window C	320
Window D	370
Internal curtain	100
External shading	250

where:

C_I is the initial investment cost needed to purchase and install the window, the opaque wall and, if present, the shading system [€];

$C_{a,i}$ is the annual running cost during each year i , which is the expenditure for the energy needed for heating, cooling and artificial lighting and the maintenance cost, if present [€];

t is the length of the calculation period [years];

r is the real interest rate [-];

$V_{f,t}$ is the residual value of the components at the end of the calculation period [€].

The initial investment cost C_I of each configuration was calculated on the basis of European average prices (in this respect we conducted a specific market analysis). The adopted values, reported in Table 6, are in good agreement with literature values [50] and have to be assumed as the average specific turnkey costs including all the needed accessories/labour and excluding VAT. In detail, for the windows, the various types of glasses are considered coupled to an openable high-performance aluminium frame. For the solar

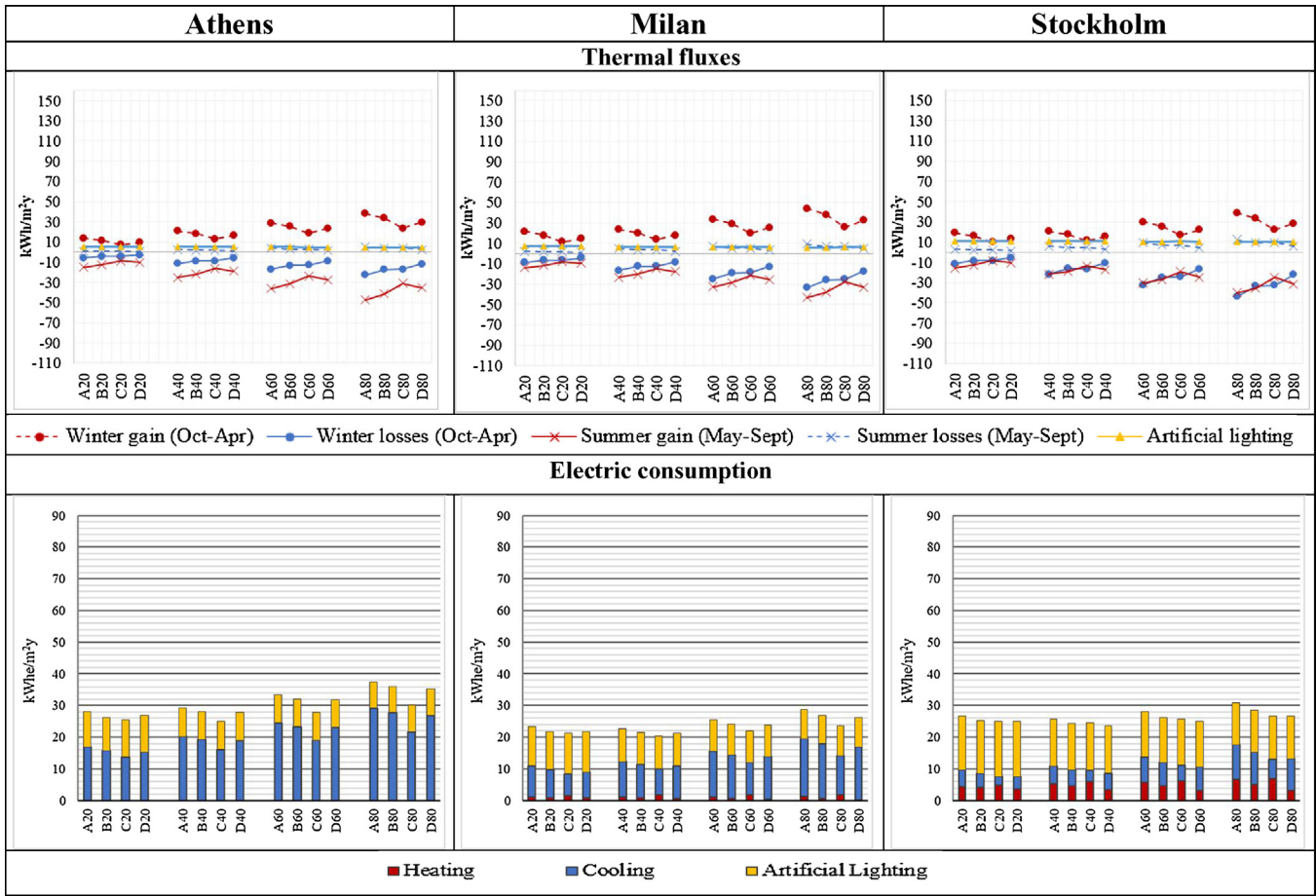


Fig. 7. Thermal fluxes and electric consumption with external shading.

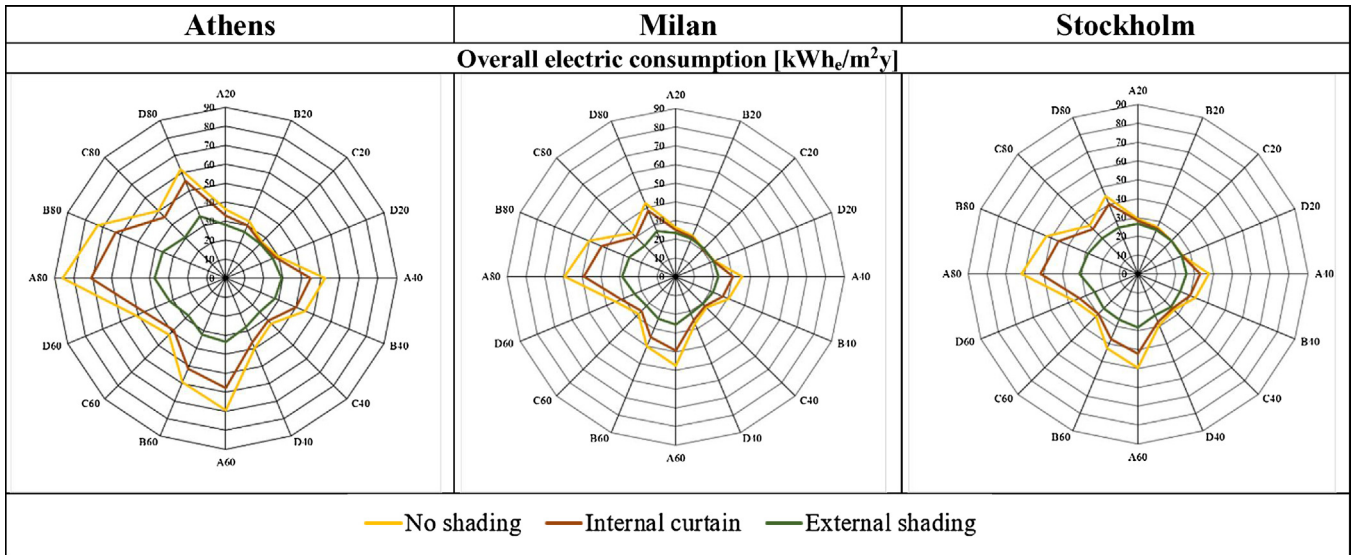


Fig. 8. Overall electric consumption for the three locations without and with shading.

shading systems, a roller curtain was supposed for internal application and movable aluminium blinds were assumed for external positioning; as already introduced, in both cases the shading elements are supposed to be equipped with an automated control system and also the cost of the necessary electric components is included.

Since the variation of the glazed surface implies also a different area of the opaque wall on the façade of the analysed room, we also estimated a reference turnkey cost for this wall. In detail, considering the layers of the wall described in Section 2.1, we established a specific cost of 150€/m² which represents the average value resulted from an assessment carried out for different types of insu-

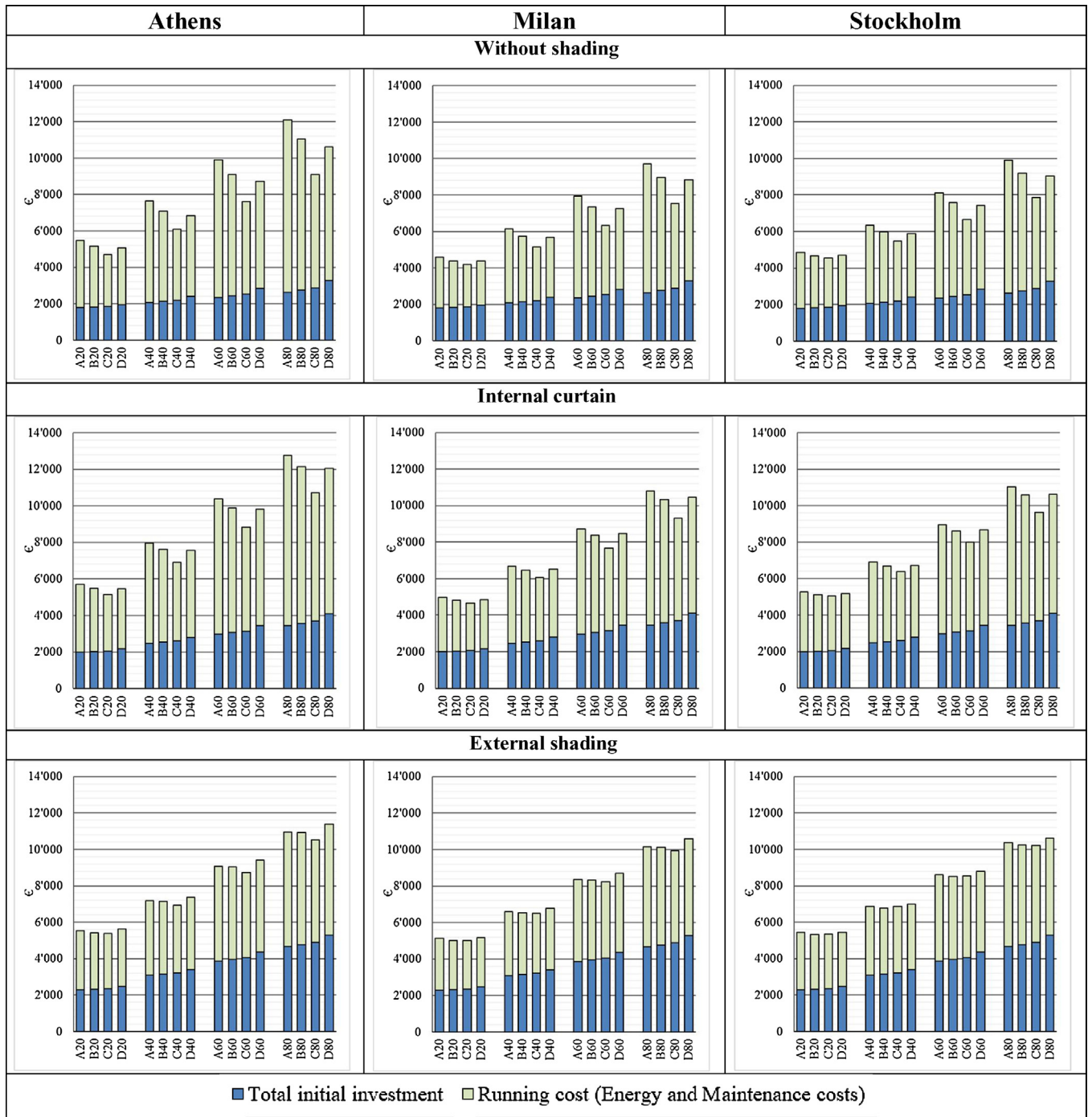


Fig. 9. Global cost for all analysed options.

Table 7
Reference parameters for the economic analysis.

Parameter	Unit	Value
Electricity cost	[€/kWh]	0.18
Rate of annual increase of electricity cost	[%]	2.0
Real investment rate (r)	[%]	3.0

lated brick walls with a thermal transmittance around $0.3 \text{ W/m}^2\text{K}$ (considering the typical costs of the construction sector on the European market) [51]. We finally calculated the total investment cost for each analysed option based on the combination of different surfaces of opaque, glazed areas and shading systems.

Subsequently, to estimate the annual running cost $C_{a,i}$, the average price of the electricity consumed by HVAC and lighting systems was derived from data given by EUROSTAT, as the average tariff in Europe for tertiary sector [52].

The other fundamental assumptions for the calculation of the actualized $C_{a,i}$ are summarized in the following table (Table 7).

In these computations the energy consumption of the moveable shadings was considered negligible, since involved powers and energy demands are very small.

To the annual running costs, one should add also maintenance: the need of maintenance for insulating windows or solar shading systems is strictly related to the specific technological solution and to the climatic context (e.g. amount of rainfall, wind speed, air

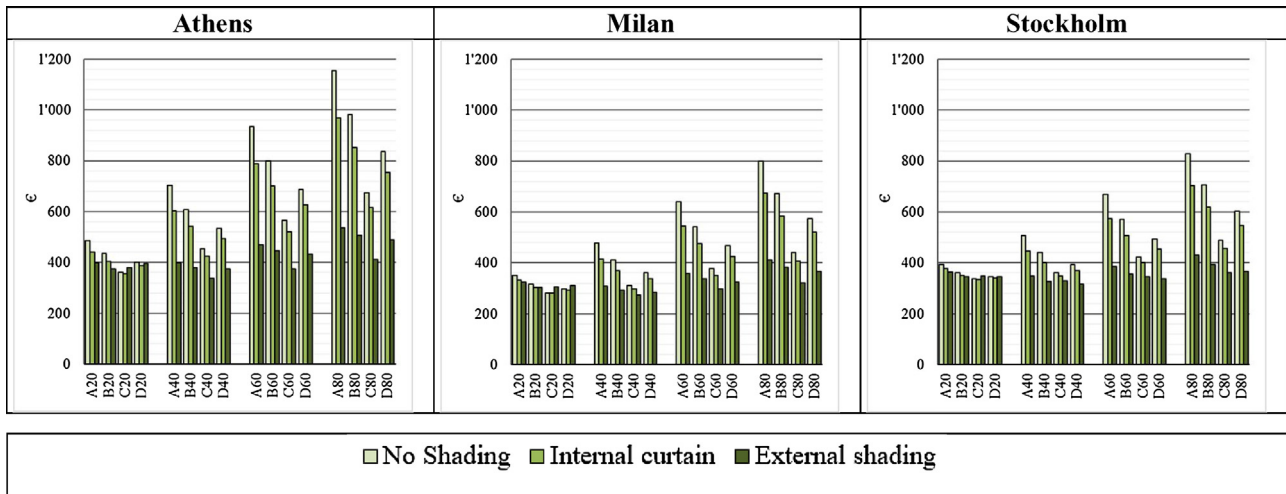


Fig. 10. GHG emission cost.

Table 8
Reference parameters for the SCC analysis.

Parameter	Unit	Value
CO ₂ emission factor	[kgCO ₂ /kWh _e]	0.453
Cost of CO ₂	[€/tCO ₂]	50

temperatures to which the window/solar shading is subjected). In general, maintenance costs of a glazed surface can be substantially related to glass cleaning, while windows components – including shading systems – require additional cleaning due to the presence of blinds/curtains (which entail supplementary costs for mechanical/electrical parts). Taking these factors into account, for the scope of the present evaluation we assumed a reference value of 7 € per m² of windows every year for solutions without shading systems and of 12 €/m²year for the ones equipped with solar shading systems (according to the figures reported in [53] and in [54]). These costs vary from 1.8% to 3% of the assumed investment costs and are within the range stated by [55] for glazed facades and double skin facades equipped with solar shading systems.

For opaque walls no maintenance is supposed within the reference calculation period, which length was set equal to 30 years. This value is considered equal to the reference lifespan of the building components, such as windows or solar shading systems, as suggested in [49] and [56]. Because of this, the residual value of the components at the end of the calculation period $V_{f,t}$ is set to 0 and thus neglected in the calculation. The global cost C_G was therefore obtained adding up the initial investment cost C_I and the annual running cost $C_{a,i}$, actualized for each year of the calculation period. The results are summarized in Fig. 9.

In general, for windows with glazing type A and B, we can state that although the use of internal and external shadings entails an increase in the investment cost up to respectively 31% and 78%, it simultaneously allows for a reduction in running costs for WWR equal or greater than 40%, with a more significant saving in hot climates. As already introduced, the impact of solar gains and thus of the related cooling energy demand on the annual energy cost is predominant on heating and artificial lighting costs if a shading system is not present and if WWR is equal or higher than 40% (Fig. 5). More in detail, the reduction in operating costs due to internal shading is on average slightly below 10% while it exceeds 30% for external shading. However, as shown in Fig. 9, this reduction is not always enough to balance the initial investment, especially in configurations with a low WWR. From a purely economic point of view, shadings are not cost effective in cold locations, such as Stockholm and Milano, and in the presence of glazing with low g even in hot

climates. In these cases, the cost reduction on cooling loads thanks to the shadings doesn't compensate for the extra-cost on investment. In these regards, in all three considered climates, the most cost-effective solution is represented by the use of windows with a solar control glass (Window C without shading). However, we point out that the solar control windows without shading systems are not able to avoid the discomfort due to glare.

Finally, we highlight that, also from economic point of view, regardless of the type of glass and shading system used, the WWR ratio is the parameter that most affects the operation cost of the building.

4.2. Cost of greenhouse gas emissions

According to EU Regulation [25] an exhaustive macroeconomic calculation requires to include greenhouse gas emissions in the global cost. This is obtained by multiplying the overall annual greenhouse gas emissions with the expected prices per ton of CO₂ equivalent. There are two main references for monetizing a ton of CO₂: its market value – resulting from the quotation of the ETS (Emissions Trading System) and the Social Cost of Carbon (SCC). The latter provides a comprehensive estimate of climate change future effects, as it monetizes the marginal benefit of reducing one metric ton of CO₂. In detail, it is equal to the stream of future damages due to an additional unit of carbon emissions in a particular year, discounted to the present day according to a standard financial calculation [57]. A recent US Government's research [58] estimated values from 2010 to 2050, with a SCC for 2010 equal to 24.75 €/t and 39 €/t, calculated respectively with 3% and 2.5% discount rates. Different discount rates are chosen because small variation of this parameter has a high impact on the final cost of CO₂. Indeed, generally adopted calculation models consider the effects of CO₂ emissions to last for hundreds years, leading to very long discounting periods. Nevertheless, a few works – e.g. the IPCC Fourth Assessment Report [59] and EPA's technical support document [60] – suggest that, for intergenerational cost-benefits analyses discount rates generally should be lower than 3%. Thus, in compliance with the value calculated by Johnson et al. [61], in this paper we consider a discount rate equal to 2% and an average cost of 50 €/t for the entire calculation period (Table 8).

The total cost of GHG emission for each analysed option was thus estimated in the selected calculation period (30 years), based on the above-mentioned parameters, as reported in the following figure (Fig. 10).

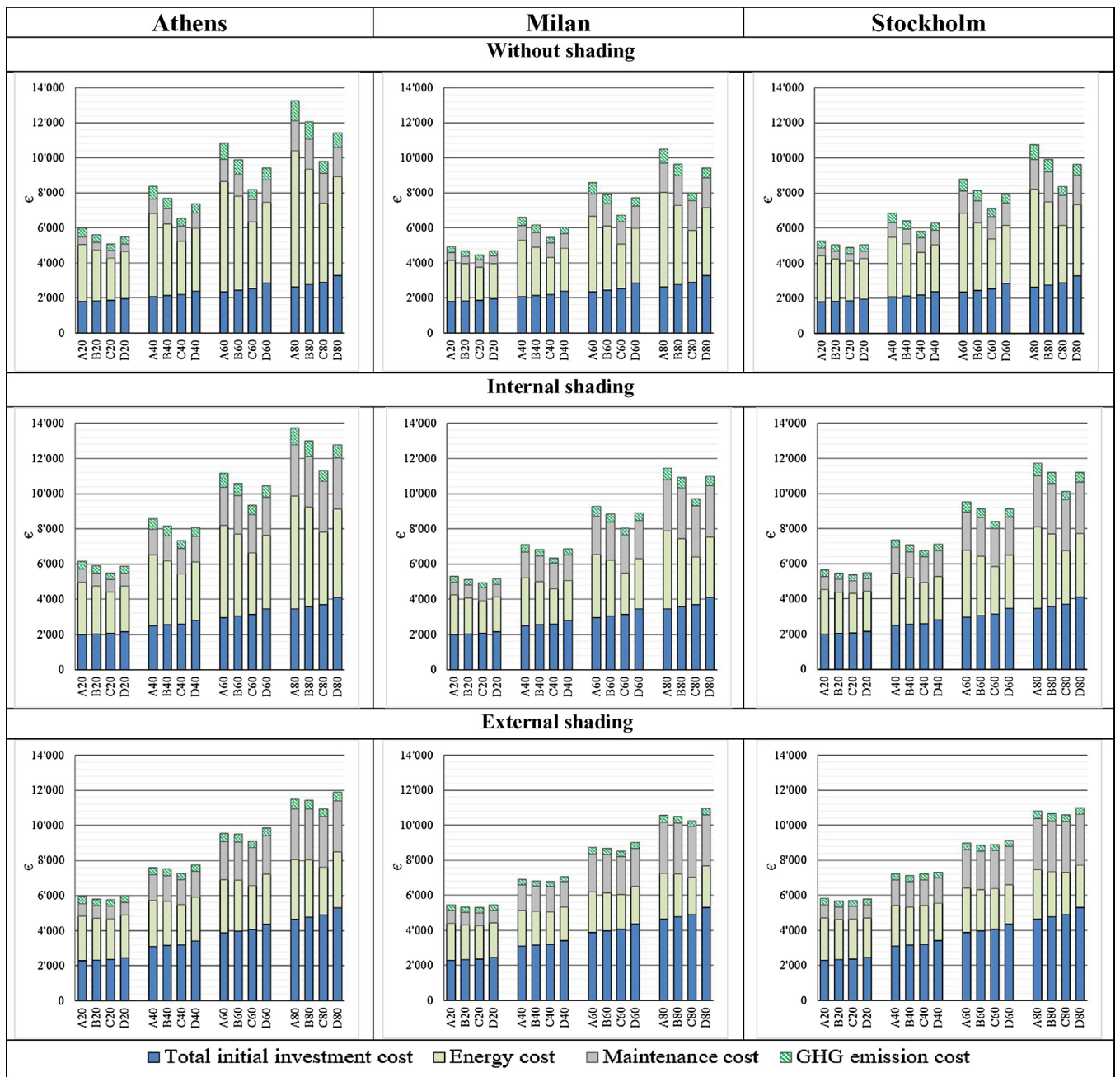


Fig. 11. Global cost and GHG cost for all analyzed options.

As it can be noted, for WWR equal or greater than 40% the use of external shadings allows a considerable saving on CO₂ emission (and in its related economic value) in all cases.

4.3. Final economic evaluations

In order to provide a comprehensive economic assessment, all above-mentioned cost items (investment cost, energy cost, maintenance cost and GHG emission cost) were added and represented in Fig. 11.

The analysis of the above-reported total costs confirms that the application of motorized solar shading systems is cost effective in cooling-dominated climates (i.e. Athens) for WWR equal or higher than 40%, in the presence of type A and B glazing. As already stated, for lower WWR and in cold climates the cost saving on the cooling demand generated by the shading doesn't compensate for the

higher initial investment needed. Similarly, in presence of solar control glazing, the use of shading is never convenient compared to the base case without shadings, since the extra cost of such a glazing is low compared to the one of the shading devices.

For WWR equal or greater than 60% and with A-type glass, the total final cost in Milano and Stockholm with external shading is very similar to the one of the base-case without shading.

For the sake of completeness further economic evaluations of the cost of discomfort are required. In fact, several studies have shown that indoor environmental conditions can have a measurable relationship to changes in office workers' performance. In particular, a comprehensive research carried out by the California Energy Commission [61] demonstrated that the glare potential from windows has a significant negative effect on mental functioning performance and thus on productivity. In detail, experimental test demonstrated that the greater is the glare from windows, the

worse is the office worker performance, with a decrease on average from 10% to 20% when glare is present. However, as previously introduced, it must be considered that, in order to minimize the effect of glare, users may freely adjust their position and view, by which is typically possible to reduce the *hours of intolerable glare* by 15% to 80% [41] depending on the user movement/adjustment freedom and on the characteristics of the furniture in the office. Therefore, in this work we assumed that, for solutions without shading systems, during the periods characterized by glare index (on office users) higher than 28 (see Table 5), an average decrease of the productivity of 15% occurs during 50% of the time. In fact, we assumed that each user could reduce the glare by an average value of 50% by adjusting its position.

Based on these hypotheses, considering the average labour productivity in Europe in the tertiary sector, assumed equal to approximately 30 €/worked hour [62], the cost of discomfort due to glare varies approximately from 300 €/year (Milan, WWR 20%) to 660 €/year (Stockholm, WWR 80%) for each office worker. Assuming the presence of two workers in a reference room, the total cost of discomfort for the entire office varies from 600 €/year to around 1'320 €/year.

In conclusion, even if the discomfort cost is influenced by many variable factors – such as positioning of the workers within the office room or presence of external elements (e.g. other buildings, trees, etc.) which partially limit the glare – it surely has a non-negligible economic impact. On a 30-years lifespan, the cost of discomfort due to the glare can be much higher than all other considered costs, thus demonstrating the cost effectiveness of every kind of motorized solar shading device.

5. Conclusions

This paper analyses the influence of windows' properties (e.g. geometrical, optical and thermal) and the application of solar shading devices on the energy consumption of a reference room, in three European climates. We analysed energy consumption for heating, cooling and lighting, according to the main boundary conditions, by means of the building energy simulation tool EnergyPlus.

In general, the research demonstrated that there is a huge negative impact of solar gains on the yearly energy balance of modern office buildings, where low U of the envelope limit heat losses and thus enhance overheating even in cold climates. Because of this, the most reasonable solution is to limit the WWR or to use external solar shading devices. The latter solution is always energetically convenient for WWR equal or higher than 40%, while from a global-cost perspective the best cost-effectiveness is achieved using a solar control glazing without any shading. If, however, we take into account also the cost of discomfort due to glare, the use of solar shading devices emerges as the most convenient option in all analysed cases.

On the basis of our present results, one can establish some basic design rules that minimize the overall energy performance of office buildings:

- WWR is the parameter that mostly affects energy and cost savings: a decrease in WWR translates into an increase of cost-effectiveness, in terms of reduction of the overall energy consumption and of the global cost. Among the four analysed WWR, a value equal to 20% emerges as optimal in the three analysed climates from an energy and economic point of view;
- in terms of energy savings, a movable external shading is, on average, the most appropriate solution – even if, with WWR equal to 20%, achievable savings are reduced especially in case of solar control glazing;

- from an energy point of view, regardless of the use of a shading systems, windows with low g and high τ_v ($\tau_v/g > 1,25$) should always be used in hot climates;
- the triple glazing with external shading, from the energy point of view, is most effective only in cold continental climates (Stockholm), for WWR between 20 and 60%;
- in the analysed climates, a slight increase in artificial lighting and heating consumption due to the application of shading systems is always much lower than the decrease in cooling consumption;
- in terms of global-cost saving, a high spectrally-selective glass, without shadings, is, on average, the most cost-effective solution;
- the use of external shading systems with extra-clear glazing (type A), for WWR equal or higher than 60% allows to achieve almost the same economic results as high performance spectrally selective glazing;
- the use of shading devices increases the comfort level of the workers and results in an increase in productivity, the economic value of which can be higher than the one of all other running costs;
- in terms of overall cost, including also CO₂ emissions and workers' productivity, solar shading devices are the preferable solution in all analysed cases.

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