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The influence of daylighting in buildings with parameters nZEB: application to the case study for an office in Tuscany Mediterranean area

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Abstract

The paper deals with the contribution of the consumption for lighting on the global energy consumption, referred to the case study of an office building defined by the Italian Heat Technology Committee, to which the reference values nZEB for thermal transmittance and solar control were applied.
The analysis highlights the importance of using daylight control systems to reduce the energy need and achieve the nZEB standard. Improving the use of daylight in buildings results in an energy saving strategy because lighting accounts for approximately 6 to 46 % of the global electric energy consumption.

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Keywords: nZEB; daylighting; energy for lighting; office buildings, façades

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Nomenclature

ψ	Linear thermal transmittance of thermal bridge, W/(mK)
U	Thermal transmittance, W/(m^2K)
g_{gl}	Solar factor (-)
τ_v	Light Transmission factor (-)
g_{gl+sh}	total solar energy transmittance (-)
ε	Emissivity (-)
$A_{sol,est}$	Solar summer equivalent area (m^2)
H'_T	Average transmission heat transfer coefficient, W/(m^2K)
ρ	Reflectance (-)
ADF	Average daylight factor (-)
EP_{gl}	Total primary energy demand, (kWh/m^2year)
EP_L	Primary energy demand for energy lighting, (kWh/m^2year)
$F_{P,nren}$	Non-renewable primary energy factor of energy carrier (-)
Ra	Color Rendering Index

1. Introduction

The drastic reduction of the winter and summer thermal loads, due to the improvement of building envelope performances, caused by the provisions adopted since the 90's, led to the current definition of "nearly zero-energy building- nZEB": a building that has a very high energy performance, where the amount of energy required should be covered to a very significant extent by energy from renewable sources [1].

In this scenario, the energy consumption for lighting can be significant in front of the other components of the energy balance.

Offices are classified among the buildings with the highest energy consumption, in particular for lighting. Therefore, improving the use of daylight in buildings results not only in healthier working conditions for users, but also in an energy saving strategy since lighting accounts for approximately 19% of the global electric energy consumption [2, 3]

Depending on the application, with an installed lighting power density of 10 to 30 W/m², a yearly energy consumption of 20 ÷ 25 kWh/m²y can typically be found in commercial buildings [4].

Concerning offices, the EIE EL-TERTIARY project for monitoring electricity consumption in the tertiary sector [5] has shown a significant difference by country: the energy consumption for lighting is on average about 23% of the total energy consumption, with values between 10 and 35 kWh/m²y (total energy consumption variable about from 25 to 350 kWh/m²y); the correspondent installed lighting power was variable from about 3 to 25 W/m^2.

To reduce this energy consumption, many researches, also conducted in recent years, have shown that daylighting can play a key role, because it is essential for comfort, health, well-being as well as for better activity and productivity: the goal is to appropriately integrate daylight with electric light to achieve a considerable reduction in lighting usage. Ihm et al. reported that daylighting controls can result in significant lighting energy savings ranging from 30% to 77% [6].

According to Dubois and Blomsterberg, in North Europe, the actual average electric lighting use is approximately 21 kWh/m^2year, but some researches have shown that daylight-linked lighting control systems, such as automatic on/off and continuous dimming, can reduce the electrical energy consumption in office buildings to 5 ÷ 9 kWh/m²year [7].

Furthermore, Xu and Su showed that it is possible to reduce the energy for lighting in offices from 30 to 90% depending on the illuminance levels, exposure, control strategies and different lighting schedule [8].

With regard to Italy, yearly electricity consumption for lighting in tertiary buildings is about 30 kWh/m^2year [5]; according to Santini et al. [9], the total yearly electricity consumption of offices in climatic zone D is evaluated in 125

kWh/m^2y (122 kWh/m^2year in Florence); therefore, electricity consumption for lighting may be about 25% of global value.

The energy consumption for lighting is considered in the recent Italian legislation that concerns general criteria, calculation methods and minimum requirements for the design and construction of energy-efficient buildings in conformity to the European standards [10]. Within this legislation context, the building Energy Performance (EP_{gl}) of the buildings is expressed by the global primary energy demand divided by the conditioned area; this index contains the primary energy demand for artificial lighting EP_L (in kWh/m^2 year).

For the purposes of energy classification, the above parameters are converted into non-renewable primary energy by using the appropriate non-renewable primary energy factor of energy carrier $f_{p,nren}$, that for the electrical energy is assumed equal to 1.95 in Italy.

The calculation of the electricity needs for lighting is carried out according to the standard EN 15193 [11]. To this scope, they consider the employment parameter according to EN ISO 13790 [12] and the use of daylighting and automatic control systems of class B according to EN 15232 [13].

The natural light is correlated to the luminous characteristics of glazing by the parameter τ_v light transmittance.

However, the light transmittance is strongly influenced by the solar factor ggl according to EN 12464 [14]: without screen, it has to be ≤ 0.35 as prescribed by the criteria and general requirements of the energy performance of buildings [10]. Moreover, also with solar protection devices, combined with glazing, the total so-lar factor for energy transmittance g_{gl+sh} must be ≤ 0.35.

Furthermore, according to the Italian Ministerial Decree 11 January 2017 [15], for windows with orientation from SSE to SSW, it is required shielding performance of class 2 or better according to EN 14501 [16], from 10:00 to 16:00 of December 21 and June 21.

In many cases, these shielding devices are placed outside the building façade and, according to Zuccherini et al., they are becoming widespread in Italy, since they are fundamental for energy saving and also for the restyling of facades and for acoustic protection from outdoor noise [17].

Regardless of the energy aspects, the Average Daylight Factor ADF must still be greater than 1-2% (according to the destination of the room), with a color rendering index $Ra \geq 80$.

Finally, to reduce energy consumption for artificial lighting, the Ministerial Decree 11 January 2017 imposes the use of lamps with an efficiency not less than 80 lm/W with $Ra \geq 90$, and the use of home automation systems assisted by sensors of presence [15].

Therefore, the purpose of the study is to highlight the contribution of energy lighting (EP_L in kWh/m^2 year) on the global primary energy demand (EP_{gl}) in the case study of an office [18] to which the reference values nZEB for thermal transmittance and solar control were applied according to the recent Italian Ministerial Decree [10].

In this context, the role played by the natural light can be important to reduce energy consumption for artificial lighting without renouncing to visual well-being.

At this purpose, we have taken into consideration the above aspects applied to the case study, placed in Tuscany, with the climatic data of the town of Florence that represents the Mediterranean climate of central Italy [19].

In particular, Proxy HDD (Heat Degree Days), winter climatic severity variable (25% weight), and Proxy CDD (Cold Degree Days), correlated with the consumption of electricity for summer cooling (5 weight %), of the Florence weather station, are considered by the Italian National Agency for New Technologies, Energy and Sustainable Economic Development (ENEA) to define the super index parameter that combines indicators of some important variables to the performance of the various sectors of energy end-use consumption of the Italian energy system [20].

2. Description of the case study

The case study consists of a detached office building named "Building 5A", drawn up in March 2010 by the Italian Heat Technology Committee – CTI [18], in order to test the software tools for energy performance certificate with national reference buildings (Fig. 1).

The office is a two-story building composed of ten air–conditioned rooms, with the entrance oriented to South, and with the services and the staircase leading to North.

Tables 1 and 2 summarizes the general data of the building.

To calculate the energy consumption, the building and the air conditioning system were modeled in Design Builder® software (version 5.01.016) with Energy Plus version 8.5. The calculation of the electricity needs for lighting correlated to daylighting is carried out by Relux® software.

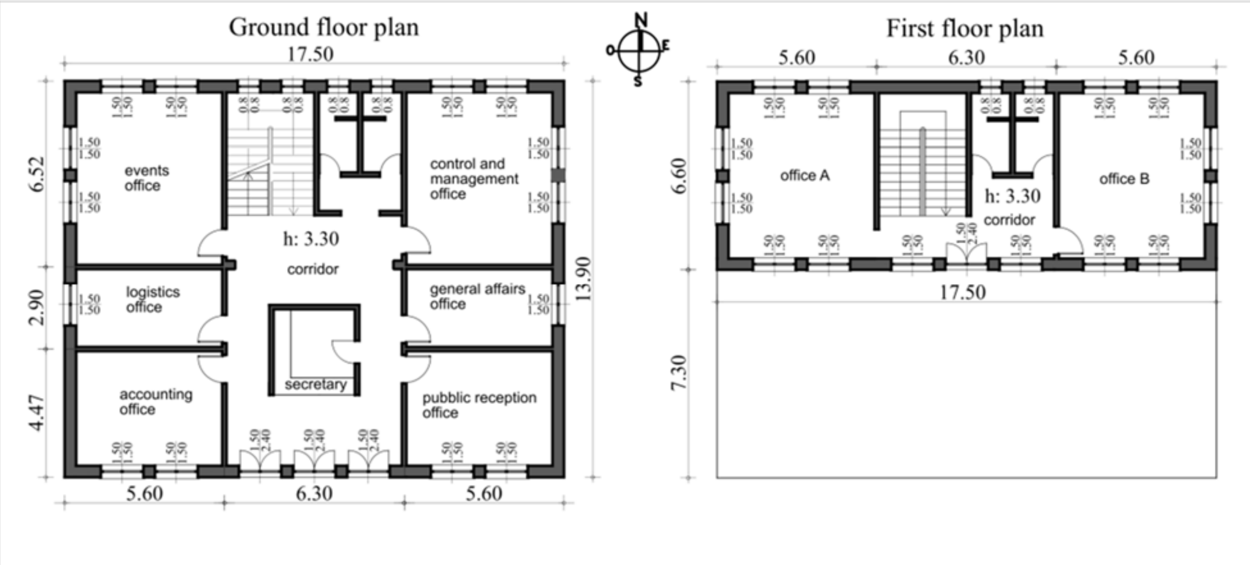

Fig. 1. Building Office from Italian Thermotechnic Committee [18].

The HVAC system consists of a variable refrigerant flow air-conditioning system (VRF - Variant Refrigerant Flow) that varies the refrigerant flow rate using variable speed compressor in the outdoor unit, and the electronic expansion valves (EEVs) located in each indoor unit; moreover, fresh air is provided by Dedicated Outdoor Air System (DOAS) with heat recovery and electric preheat coil.

Air handling unit DOAS is a system that brings fresh outdoor air indoors to improve air quality without reducing energy efficiency, designed specifically for VRF systems and insulated to decrease heat flow and sound levels.

Indoor units operate to satisfy a heating or cooling load in a zone based on a zone thermostat temperature set point. Direct-expansion (DX) cooling and heating coils are specified and used depending on the operating mode required.

Outside air can be provided to the zone continuously even when the coil is not operating. The bathrooms, using mechanical ventilation system, are not conditioned.

The thermal transmittance of the building envelope (walls, roof, floor, windows) has been calculated on the basis of the reference CTI office building (characteristic, surfaces, etc.).

As for thermal bridges, those gathered in the standard EN ISO 14683 [21] have been used referring to the external thermal insulation of the envelope.

In Table 3 the analyzed thermal bridges are reported. Based on CTI building, thermal transmittance of all the components with external insulation have been calculated and compared with nZEB limit values (2019/2021) reported in Table 4 for climatic zone D (Florence).

Table 1. Geometric properties of the reference building of the Italian Thermotechnic Committee CTI [18].

gross conditioned volume V_G	(m^3)	1,309.4
exterior envelope surface S_G	(m^2)	1,122.6
compactness ratio S_G/V_G	(m^{-1})	0.86
total net floor surface of conditioned space A_f	(m^2)	289.2
net conditioned volume V	(m^3)	998.0
windows surface S_w	(m^2)	81.2
wall exterior surface S_{wall}	(m^2)	256.0
gross exterior surface S_{Gwall}	(m^2)	344.3
window /envelope wall ratio S_w/S_{wall}	(-)	0.317
window/ net floor surface ratio S_w/A_f	(-)	0.281

Table 2. Data relating to users and HVAC system (elaboration from CTI [18]).

crowding index	Persons/m^2	0.06
hourly air volume per person	m^3/(h*pers.)	39.6
average outdoor air in working hours	h^{-1}	0.74
heat recovery efficiency	-	0.8
set point air temperature for heating	(°C)	20
set point air temperature for cooling	(°C)	26
Schedule for occupancy	Until: 08:00, 0.0 Until: 17:00, 1.0 Until: 24:00, 0.0 For: Weekends Holidays Until: 24:00, 0.0	
Sensible heat gains (UNI c, 2008)	(W/m^2)	6
HVAC systems	VRF (Air-Cooled), DX, DOAS, Heat Recovery	
hours of activation	11 h/day (7:00 to 18:00)	
energy source	Electricity	

Table 3. Analyzed thermal bridges.

Thermal bridges	Linear thermal bridge coefficient ψ (W/mK)
Ground junction	0.75
Roof junction	0.15
Pillar	0.15
Corner	0.15
Floor junction	0.10

Table 4. nZEB limit values for thermal transmittance and values used for energy simulation (W/m^{2}K).

	nZEB value	Value used
Wall	0.29	0.120
Ground floor	0.29	0.261
Roof	0.26	0.236

Table 5. Case study – Window to Wall Ratio and correlated energy performance.

	Total	North	East	South	West
Gross Window Opening Area (m^2)	81.13	21.78	11.25	36.87	11.24
Gross Window-Wall Ratio (%)	23.56	19.76	18.28	33.46	18.02
$A_{sol,est}$ for solution 1 (m^2)	17.91	3.72	3.44	7.31	3.43
$A_{sol,est}$ for solution 2 (m^2)	16.55	3.44	3.18	6.76	3.17
$A_{sol,est}/A_f$ solution 1 and 2 (-)	0,057 ÷ 0.062 > 0.03 limit value				
H'_T (W/m^{2}K).	0.33 < 0.53 limit value				

As for transparent components, thermal transmittance has been calculated in order to achieve the limit values of nZEB standard equal to 1.8 W/m^{2}K.

Chosen windows have the following performances:

- wooden frame with U_f = 1.4 W/m^{2}K;

and two different glasses:

- double glass (6/16/6, ε=0,2) with g_{gl} = 0.61 and τ_v = 0.78;
- double solar control glass (6/16/6, ε=0,2) with g_{gl} = 0.31 and τ_v = 0.47.

For the shading systems, a solar factor $g_{gl+sh} \leq 0.35$ have been guaranteed for nZEB target according to the Italian Ministerial Decree [10].

The analyzed solutions combine two different shading systems described by Carletti et al. [22, 23]:

- Double glass with external drape shading system with g_{gl+sh} = 0.335;
- Solar control glass without shading system with g_{gl+sh} = 0.31.

Other parameters, summarized in Table 5, have been calculated for the evaluation of the energy performance of the office according to the Italian Ministerial Decree [10]:

- $A_{sol,est}$ solar summer equivalent area (m^2); taking in account incident solar radiation, solar characteristics of glazing and shading;
- $A_{sol,est}/A_f$ (-) that has to be ≤ 0.03 (0.04 for public offices);
- H'_T average coefficient of heat transfer, that in this case has be ≤ 0.53 (W/m^{2}K).

The values in Table 5 show that the office has a good H'_T thermal transmission parameter but, on the contrary, the window area is too large, with consequences on daylighting and energy consumption for lighting.

This situation is obviously particular and limited to this case study but it is interesting to explain the possible relations between energy performance, these dimensional parameters and the typology and technology of building (compactness ratio, surface of window, solar factor, etc.).

3. Evaluation of the energy performances

The energy performance of the office is calculated by Design Builder@ software, interface graphic of Energy Plus ver.8.5.

The parameter of input and schedule for HVAC plant are show in Tables 1 and 2, while the additional assumptions are listed below:

- shading by outdoor drape (solution 1) and by control solar glass (solution 2);
- weather data set is a Test Reference Year (TRY) based on climatic data collected between 2000 and 2009 by the meteorological station "Firenze Città" [24];
- control type solar set point for solution n. 1 with external drape fixed to 300 W/m^2;
- soil temperature calculated on the basis of current climate file;
- artificial interior lighting not considered (see next section);
- DHW not considered.

With these assumptions, the results for HVAC are summarized in Table 6 for both solutions and compared to the energy use for lighting of Fig. 5.

Also, if it isn't considered the energy for lighting, these results are greater respect to existing requirement of primary energy consumption in nZEB office buildings for Italian climatic zones C and D, and equal to 54÷57 kWh/m^{2}year [25].

This is due to the high compactness ratio (0.86), the higher window surface/floor area ratios (> 0.25) and between this and the exterior wall surface (0.24) (Table 5).

The energy use for lighting is calculated taking in account the daylighting.

The daylight illuminance level in a room depends on many factors, including location (latitude and longitude), external obstructions, sky condition (clear sky, overcast, etc.), sun position (hour, day and month), size and glass transmittance of windows, type of window shades and control, reflectance of interior surfaces, albedo effect.

According to Yun et al. [26], the consumption of electric lighting depends on daylight illuminance level, illuminance set point, fraction of room controlled and type of lighting control.

Table 6. Energy performance for HVAC without energy lighting.

	Total Energy solution 1 [kWh]	Energy/A_f solution 1 [kWh/m^2]	Total Energy solution 2 [kWh]	Energy/A_f Solution 2 [kWh/m^2]
Net non-renewable delivered Energy	12,101.35	40.31	11,478.07	38.23
Net non-renewable Primary Energy	23,597.63*	78.60*	22,382.24*	74.55*

*Italian nonrenewable Primary Energy Factor of electricity = 1.95

It is very difficult to keep count at the same time of all these factors and relative variables so we limited the scope of investigation to the following conditions:

- the office building has no buildings around (no obstructions);
- two type of window glasses: solution 1 with visible transmission factor $\tau_v = 0.78$ and solution 2 with solar control glass $\tau_v = 0.47$, as described previously;
- for solution 1, an outdoor white diffusing drape with $\tau_v = 0.5$ is present when direct sun irradiation enters in the interior environment;
- the following values of the average reflection factor ρ have been considered for the interior surfaces of all the rooms of the building: $\rho_{ceiling} = 0.7$; $\rho_{walls} = 0.5$; $\rho_{paving} = 0.2$;
- the calculation grid is set at the height of the working plane (h = 0.8 m from the ground) and 0.5 m from the walls;
- the sky condition considered for the calculation of the average daylight factors is CIE overcast sky.

Furthermore, the calculation of the energy consumption for artificial lighting is based on the results shown in Fig. 4 and on the following assumptions for the electric lighting system:

- fluorescent tubes with power consumption of 58 W and total flux of 5400 lumen, not dimmable (average power density = 17 W/m^2);
- type of daylighting control: on – off;
- number of fluorescent tubes installed in each room calculated with the total flux method, considering the physical properties (dimensions, surfaces' reflectance) of each room and the required minimum lighting level of 500 lux.

All lighting calculations concerning daylighting availability have been carried out with the software Relux Pro® (version 2016), already used and validated in previous studies [27, 28].

Fig. 2 shows the average values of the daylighting factor with CIE overcast sky for all the rooms of the office building. It can be noted that the average daylight factor is very high in the rooms at the first floor with larger window surface (S_w/A_f = 0.28), especially for the first solution if outdoor drapes are not lowered (τ_v = 0.78), and is always greater than the limiting value recommended by Italian legislation for offices (1 %). The solution 1 has been evaluated without the outdoor drapes because we assumed that occupiers lower the drapes only when the direct sun irradiation enters in the room. Therefore, in the calculation of daylight factor with overcast sky, the drapes are not present.

In the calculation of the energy use for artificial lighting we considered, for the whole year, the availability of daylight. The sky conditions (alternation between sunny and cloudy skies) are those corresponding to the town of Florence, and are taken from the data base of the calculation software (satellite data).

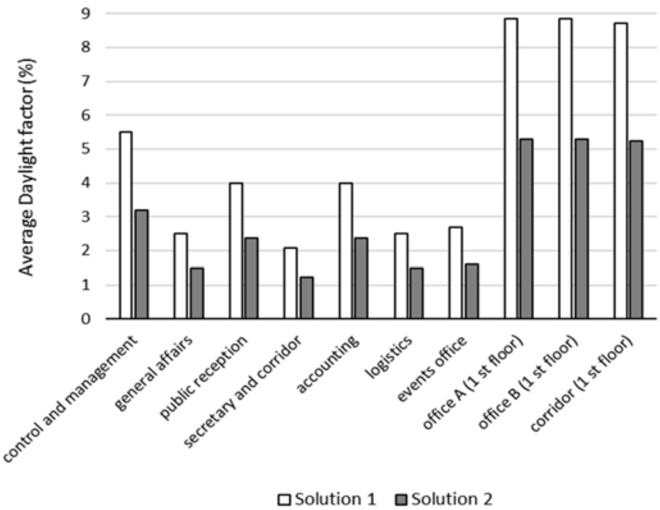

Fig. 2. Average Daylight Factor with CIE overcast sky for all the rooms of the office building.

The illuminance set point considered for the calculation of the artificial lighting need is 500 lux for all rooms and corresponds to the value given by the EN 12464 for offices [14]. In addition, the set points of 300 and 750 lux have also been considered to keep count of tasks visually difficult (such as technical drawing) or easy (such as secretary or public reception).

Relux calculates the daylight illuminance in lux with overcast and clear skies for all the days of the year and in the time interval when the office is occupied (08:00 – 13:00 / 14:00 – 17:00). With clear sky, only the diffuse component of daylight is computed. Therefore, in rooms with windows not exposed to North and with sunny days, when the direct sun radiation enters in the rooms, the illuminance level is greater that the value calculated by Relux.

To keep count of the occupant behavior, we considered that the outdoor drapes are lowered only when there is a direct and consistent entrance of direct sun radiation in the rooms. In these cases, with outdoor drapes lowered, it could be possible that the quantity of daylight entering the room is so reduced that it becomes necessary to turn the artificial light on.

To better analyze these cases, we considered the case of a single room (the public reception office at the ground floor), with windows exposed to South, in two typical hours of the year: the summer solstice (12 pm of June 21th) and the winter solstice (12 pm of December 21th). The calculations, carried out with the module Raytracing of Relux, were performed both with and without the outdoor drapes.

The aim of these simulations was to verify the amount of daylighting during a typical sunny day with and without the outdoor drapes. The average daylighting level in the four cases analyzed is summarized in Table 7.

Table 7. Average daylighting level in the public reception office.

sunny solstices	Without outdoor drapes	With outdoor drapes
	Average daylighting level (lux)	
June 21th – 12 pm	793	546
December 21th – 12 pm	10,800	967

From Table 7 it can be noted that the lowering of the outdoor drapes, analyzed within this study, does not reduce the daylighting level below the set point of 500 lux and consequently does not induce to turn the artificial lighting on.

Fig. 3 shows the percentage of working hours when the daylight is greater than the set point of the artificial lighting system (500 lux), with reference to solution 1 ($\tau_v = 0.78$). It represents the percentage of working hours when the artificial lighting is off.

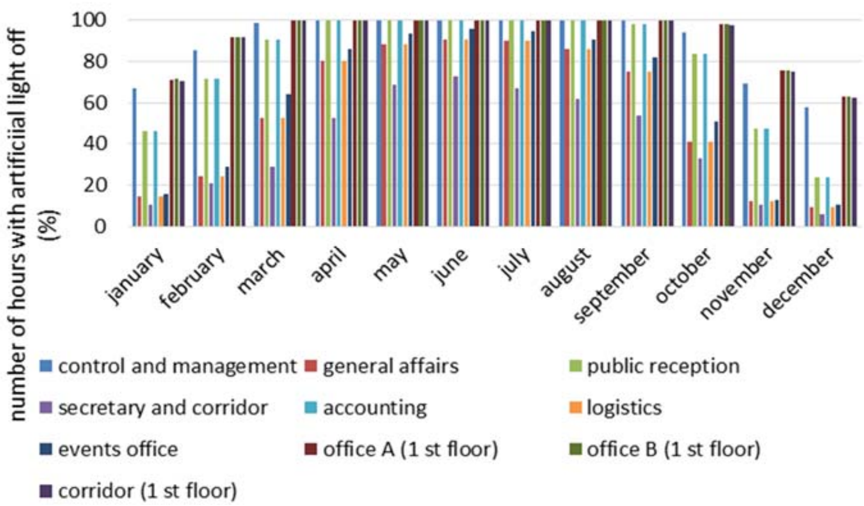

Fig. 3. Percentage of working hours when the artificial lighting is off, for solution 1 (500 lx).

Fig. 4 shows the total energy use of the building for artificial lighting for each month of the year and for the two solutions considered, in kWh/m^{2}month, while Fig. 5 shows the total energy use of the building for artificial lighting for all the year (kWh/m^{2}year).

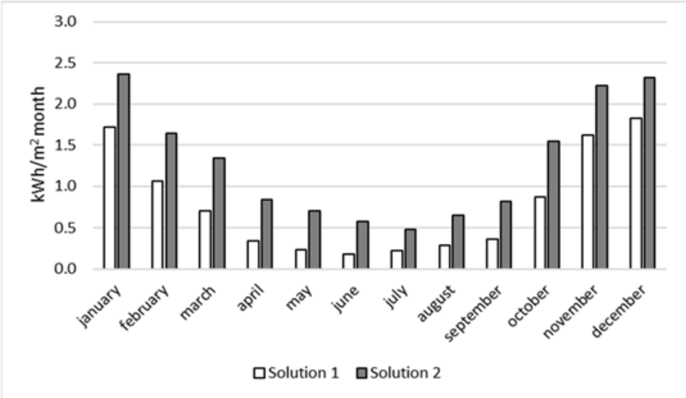

Fig. 4. Total energy consumption of the building for artificial lighting for each month of the year and for the two solutions considered (500 lx).

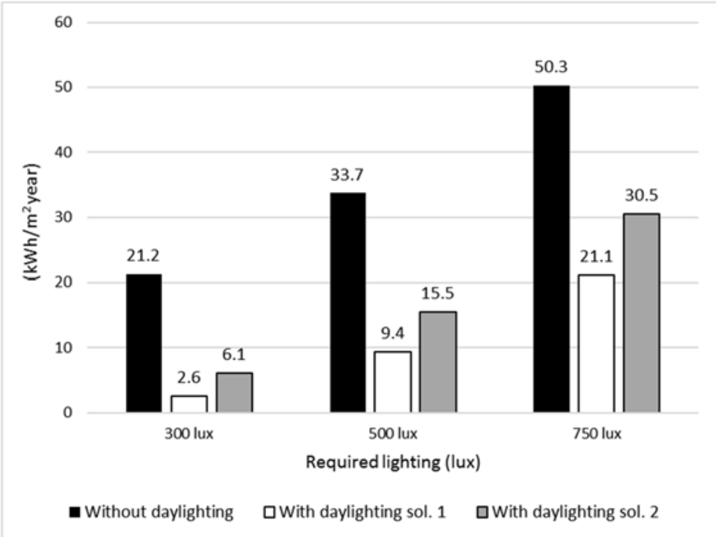

Fig. 5. Yearly total energy use of the building for artificial lighting and for three set point of artificial lighting level.

Fig. 5 considers both the solutions analyzed and also the case of artificial lighting system not controlled by the daylight level. This last data is representative of the case when the artificial lighting is always on during all the working period of the year and indicates the maximum energy consumption to reach the set point of illuminance.

It can be noted that the values of 9.4 and 15.5 kWh/m^2 year, referred in Fig. 5 to solutions 1 and 2 and to the set point of 500 lux, are the sum of the values reported in Fig. 4 for the different months of the year.

According to Dubois and Blomsterberg [7], we can observe that an appropriate use of the daylight can reduce energy consumption for artificial lighting from about 1/2 (solution 2) to less than 1/3 (solution 1). Moreover, with the power density of 17 W/m^2, without daylighting, the energy consumption is in the range from 21 to 50 kWh/m^{2}year, consistent with the previously cited values [4, 5].

The conversion of energy use for lighting in non-renewable primary energy is done in Fig. 6.

4. Comparison of energy consumption for lighting and HVAC

Fig. 6 shows the results of the comparison between the energy use for HVAC and lighting in terms of non-renewable primary energy for solutions 1 and 2, and several illuminance levels with and without taking in account the daylighting (only for 500 lx).

It can be observed that the energy consumption for lighting ranges from about 6.1 to 44.4 % of total energy consumption, while without daylighting control is about 45 % (for 500 lx). These results are in accordance with European [4, 5] and Italian data [9], as well as those reported by Yu and Su [8].

In particular, if we assume for HVAC different energy source, like gas, the conversion factor in non-renewable primary energy is 1.05 and therefore the weight of energy lighting is much greater (variable about from 10 to 60 %) and daylighting control becomes more important. Also, the illuminance levels are very important for reduce energy use for lighting: from 300 to 750 lx the increase is more than 80%.

Moreover, better performances may be obtained by the solution 1, with external drape shading system, in front to solution 2 with solar control glass, because in this case the use of daylighting is always reduced.

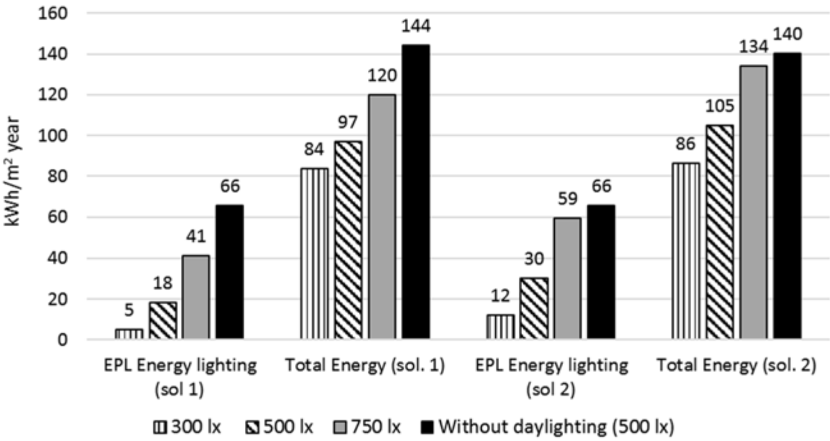

Fig. 6. Non-renewable primary energy demand for EP_L and total energy EP_{glob} for different situations (Non-renewable primary energy factor of electrical energy = 1.95).

5. Conclusion

A case study of building office was analyzed, located in central Italy, where Florence has an appropriate and significant climate for the aim of the research.

The energy performance of the building, with values of thermal transmittance of opaque component and windows in compliance with the standard nZEB, has been evaluated in terms of non-renewable primary energy for HVAC and lighting.

The energy use, equal to 97tabl÷105 kWh/m^{2}year for the solutions 1 and 2, considering daylighting, with a level of illuminance up to 500 lx, is very high with respect to the target nZEB for office buildings, which is equal to 54÷57 kWh/m^{2}year for Italian climatic zones C and D [25].

Moreover, also the energy consumption for lighting EP_L is very high if we want a lighting level over 500 lx with solar control glass with poor light transmittance (solution 2). Only if gas is used as energy source (non-renewable primary energy factor of 1.05) and taking in account the daylighting contribution the results agree with nZEB target for both solutions.

In any way, the analysis shows that it is fundamental to use daylight control systems to reduce the energy need both for lighting and for total consumption if we want to achieve the standards nZEB.

Improving the use of daylight buildings results in an energy saving strategy because lighting accounts for approximately from 6 to 46 % of the global electric energy consumption, in accordance to previous researches on this topic.

The results cannot be used to provide general solutions; however, they are useful for highlighting the importance of the reduction in lighting usage by integrating daylight with electric light.

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