Does window-to-wall ratio have a significant effect on the energy consumption of buildings? A parametric analysis in Italian climate conditions

# Does window-to-wall ratio have a significant effect on the energy consumption of buildings? A parametric analysis in Italian climate conditions

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## Abstract

Building envelope structures play a pivotal role in the energy behaviour of edifices. They influence the heat exchanges between indoor and outdoor environment and might allow a proper exploitation of solar energy. Therefore, when properly designed, they can contribute to minimizing the overall energy demand of buildings, allowing achievement of the high energy performance that is the basis of the Nearly Zero Energy Building (NZEB) concept.

In this context, window systems are generally considered as the crucial element to be correctly designed for energy efficiency purposes in view of the role they play in heat exchange processes and solar gain management.

This paper outlines the methodology and the correspondent results of an analysis which aims to search for the optimal size of the window surface, which is the size allowing minimum overall energy consumption, in an office building whose structure and configuration represent a typical reference case for the Italian building stock.

Several configurations were considered, varying the climate, the thermal features of the building envelope and the installed lighting electric power. Furthermore, the influence of a switchable shading device was assessed and the correlated comfort consideration reported.

The analyses were performed using Energy Plus simulation code and the window dimensions were evaluated in terms of the ratio between the glazed surface and the gross façade area, which is referred to as window to wall ratio (WWR).

**Keywords:** window to wall ratio; building energy consumption; solar gains; smart switchable shading devices, NZEB.

# 1 Introduction

Energy use in edifices accounts for a large percentage of total energy consumption worldwide. Globally, buildings represent the largest energy-consuming sector in the economy, with over one-third of all final energy and half of global electricity consumed there [1] . As a result, they are also responsible for approximately one-third of the global carbon emissions. In the United States, the buildings sector accounted for about 41% of primary energy consumption in 2010 [2], whereas, in Europe, buildings are responsible for 40% of energy end use and 36% of CO2 emission [3–6].

Therefore, improving the energy performance of the building stock has become one of the pivotal strategies with a view to both reducing the exploitation of energy sources and limiting climate change.

In Europe, member states are currently introducing new technical standards that are profoundly modifying the design approaches to building efficiency. EU directives also contain various important suggestions concerning the environmental performance of buildings and, despite the fact that this performance is essentially treated because of energy consumption, the importance of a more general Ecolabel ranking scheme has been largely recognized [7].

Within this framework, the topic of Nearly Zero Energy Buildings (NZEB) has received increasing attention in recent years [8–11] so that, in the recast of the EU Directive on Energy Performance of Buildings (EPBD) [3], it is specified that by the end of 2020 all new buildings shall be “*nearly zero energy buildings*”.

In the Directive, NZEB is a building that has a very high energy performance, while the residual very low amount of required energy should be supplied by renewable sources located on site or nearby. In other words, a NZEB combines energy efficient building and system design with on-site renewable energy generation [12].

As a consequence, the project of the building envelope, which affects energy flows in buildings to a very large extent, is a crucial issue with a view to achieving very high levels of energy performance. However, this is not a simple task because of the fact that the envelope is composed of different type of structures which have different effects on building energy flows (heat loss, solar gain, etc.) and have counteracting influences on the various facets of indoor comfort (visual, thermal, acoustic) [13–16] .

One of the features of the façade configuration which mostly affects the building energy efficiency is the balance between opaque and transparent elements. The relevance of this characteristic on the behavior of the façade has been demonstrated in a sensitivity analysis regarding an office building equipped with automated shading [17]. As a matter of fact, the study demonstrated that, for the analyzed typology of building, among the considered factors (e.g. window-to-floor ratio, shading transmittance, glazing type, space aspect ratio, etc.), window-to-floor ratio has a great influence on useful daylight illuminance and annual heating and cooling demand.

On the other hand, the difficulty of combining energy saving purposes and comfort needs, when designing building façade, has been largely investigated [18–20] . On balance, it was pointed out that best performing configurations change if either daylighting or energy point of view is adopted [19], concluding that an acceptable trade off might be reached by singling out boundaries for a solution space which meet both requirements [18].

The effect of the window size on thermal comfort is also analyzed in [21], where an office room was simulated in order to assess the optimal proportion of window to external wall, possibly allowing comfort conditions for the longest part of the year.

However, from a comfort standpoint, it is also worthy of note that, in actual environments, the degree of influence of the window features also depends on human behavior [22–25].

As far as the building energy performance is concerned, the influence of fenestrations has been broadly investigated [26–44]. However, more the often, these researches do not have an energy integrated perspective, being merely focused either on thermal behavior of buildings, [26–36], or on the issue of potential savings achievable in terms of lighting consumption by a better use of daylighting [37,38].

The total energy perspective, which considers the global demand owing to the most relevant end uses in actual buildings (i.e. heating, cooling and lighting), can be found in [39–44].

More precisely, most of these papers refers to a single plane office module [43] with adiabatic ceiling and floor and three adiabatic wall [39–41,44], so that the heat transfer between the room and the exterior occurs only through the single exterior wall with glazing.

Conversely, a whole building was analyzed in [42], which, on the other hand, does not consider the effect of the climate conditions. However, the results showed that, for a highly insulated building façade and for a central Europe representative climate, the minimum total primary energy demand (heating, cooling and lighting) is achieved when WWR is in the range of 35%-45%, regardless the orientation, the building surface –area-over-volume Ratio, and the efficiency of the HVAC system.

As far as shading devices are concerned, albeit they undeniably contribute to an enhancement of the complexity of the window system, their use provide considerable advantages [19,44–46] in comparison to a static fenestration; nevertheless, different typologies and control strategies can be adopted and different performance achieved, so that results are difficult to be summarized. On balance, it could be pointed out that for all the situation analyzed, façades equipped with dynamic shading showed the best performance with respect to the total energy demand, whereas the façades with fixed shading devices were the worst from the same standpoint.

In this context, considering the lack of analysis regarding the contemporary evaluation of all the main building energy end uses (i.e. heating, cooling and lighting), in a total energy perspective also focused on indoor comfort conditions, and in view of the fact that evaluations regarding the whole building and not a single room are also needed, the aim of this paper is to investigate this topic, verifying the existence of an optimal value of the window to wall ratio, WWR, which is able to minimize the global building energy need, on condition that some basic comfort criteria are always verified.

Furthermore, in order to supplement the results of the former studies [42], the purpose of the proposed analysis is also to investigate on the variation which the optimal values of WWR might undergo whether climate conditions, insulation features of the façade or luminaries characteristics change. In addition, the effect of a smart switchable shading device, which was demonstrated to be the most effective technology  [43–45], was also examined.

In short, the research activity aims to give practical information to designers and building industry, also furnishing a method that might be used to configure a proper façade structure, taking into account the factors that demonstrated to affect energy consumption the most, like, for example, the main features of the lighting system, whose influence is often disregarded during the building envelope design process.

## 2 Methods

The aim of this study is, firstly, to verify the existence of an optimal value of the ratio of the glazed surface ($S_w$), to the whole façade surface ($S_f$), the so called Window-to-Wall Ratio (WWR, Eq. (1)), designed to minimize the building overall energy consumption due to heating, cooling and lighting demands in various climates:

$$WWR = \frac{S_w}{S_f} \tag{1}$$

Furthermore, the purpose of the proposed analysis is also to investigate the variation which the optimal values of WWR ($WWR_{opt}$) might undergo whether climate conditions, insulation features of the façade or luminaries characteristics change or shading devices are installed.

In order to fulfill these tasks, typical reference buildings, singled out in previous studies [47,48], were considered and their energy performances were analyzed by means of a well-known simulation software: Energy Plus [49,50]. This tool is able to perform integrated thermal and daylight simulations, furnishing reliable results for the scope of the current analysis [42,51], also because it can be used in connection with other tools for combined assessments, characterized by different perspectives [52].

Every simulation run was set with a view to calculating the overall energy which is to be delivered to the building in order to keep the selected environmental parameters (i.e. indoor air temperature, illuminance) inside typical comfort ranges. This allows the basic comfort conditions to be satisfied, even though considerations on the actual comfort levels inside the indoor environments were also reported.

As a rule, buildings have different energy end uses, which are mainly heating, cooling and lighting. Usually they are fed by different energy carriers: electricity, methane, natural gas, etc.

The global energy consumption of the selected buildings was evaluated in terms of primary energy, using the following expression:

$$Q_G = \sum_i E_i \cdot f_{PE_i} \tag{2}$$

where:

$Q_G$ is the global primary energy consumption (kWh);

$E_i$ is the consumption related to the i$^{th}$ energy carrier (kWh);

$f_{PEi}$ is primary energy conversion factor of the i$^{th}$ energy carrier.

Two types of energy carrier were actually considered in the current analysis: electricity and natural gas; the first one delivers to the studied building the energy needed to feed cooling and lighting systems, while the second one sustains the heating demand; the primary energy conversion factors are 2.174 $kWh_{pe}/kWh_{ee}$ and 1 $kWh_{pe}/kWh_{ng}$ respectively [53,54].

Therefore:

$$Q_G = Q_L + Q_c + Q_h = 2.174 \times (E_L + E_c) + E_h \tag{3}$$

where:

$Q_L$ is the lighting primary energy consumption (kWh);

$Q_c$ is the cooling primary energy consumption (kWh);

$Q_h$ is the heating primary energy consumption (kWh);

$E_L$ is the electric consumption for lighting (kWh);

$E_c$ is the electric consumption for cooling (kWh);

$E_h$ is the natural gas consumption for heating (kWh).

When the influence of the window dimension on the energy demand of buildings is analyzed, different trends are, by and large, assessable: both heating and cooling demands rise with the window size, but conversely lighting demand decreases. Likewise, this behavior can also be inferred when primary energy consumption is taken into account.

An example of this fact is reported in Figure 1, where a typical trend of building primary energy consumption (heating, $Q_h$, cooling, $Q_c$, lighting $Q_L$ and overall, $Q_G$) versus the window to wall ratio ($WWR=S_w/S_f$) is depicted.

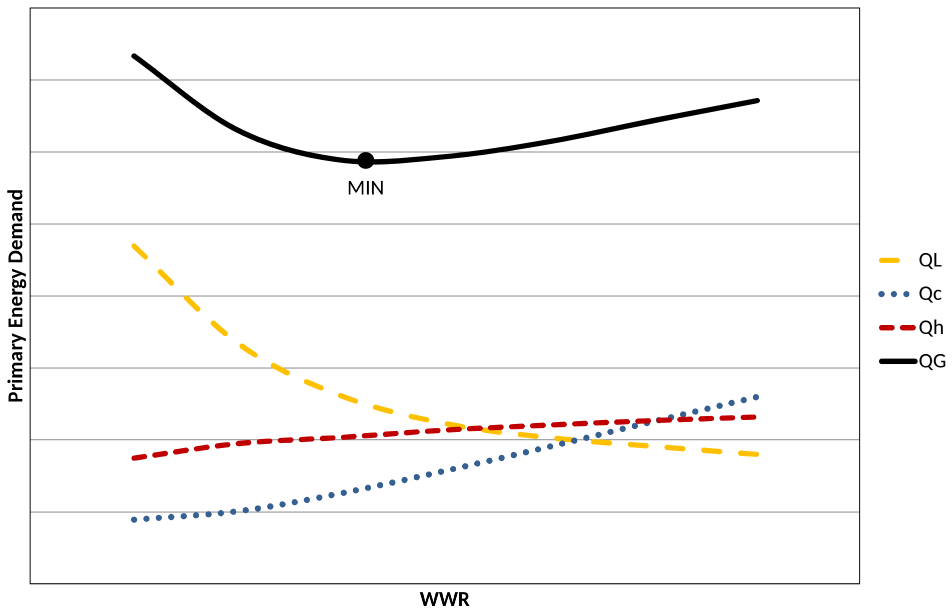



**Figure 1. Typical trend of primary energy demands of buildings versus window-to-wall ratio (WWR).**

Owing to the described different influences which window dimensions have on the various energy uses in buildings, global consumption tends to be characterized by the presence of a minimum value which corresponds to the optimum value of WWR (Figure 1).

With a view to singling out this optimal value, $WWR_{opt}$, an analysis was performed by simulating several office buildings whose façades were characterized by different values of WWR. The results of the simulation analysis were interpolated by means of the following equation (Figure 2):

$$Q_G = f(WWR) = \sum_{i=0}^{5} a_i (WWR)^i \tag{4}$$

so that a minimum search algorithm was employed to reach the designed purpose:

$$WWR_{opt} = argmin\{f(WWR)\} \tag{5}$$

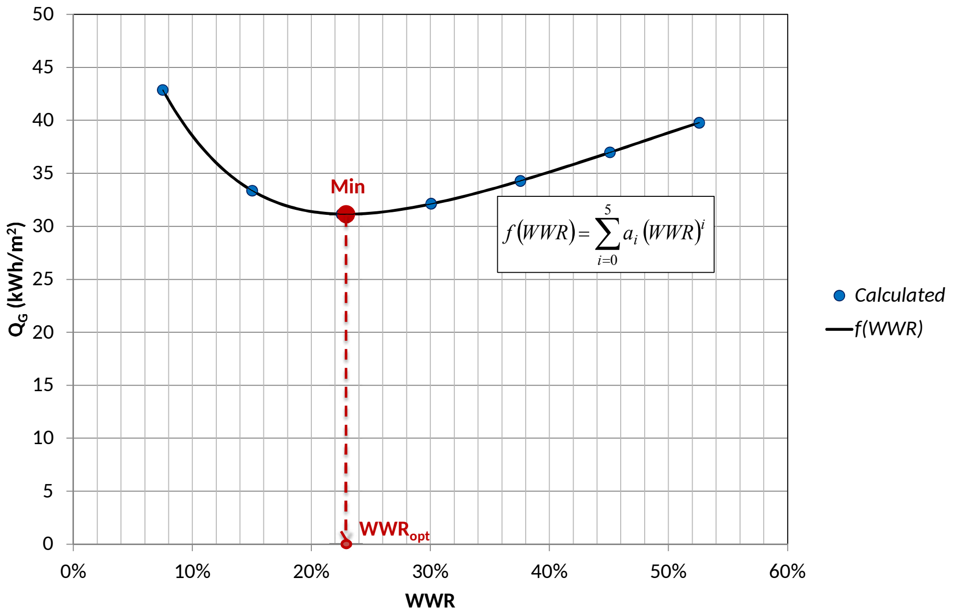



**Figure 2. Typical trend of global primary energy demand of buildings and of its regression function versus window-to-wall ratio (WWR).**

Therefore, the first step of the procedure consists in the construction of the function *f*; to reach this aim various simulations were performed changing the WWR from 0.08 to 0.53 with a regular step, so that 7 values of WWR were considered.

In regard to this aspect, it was considered that, from a global consumption point of view, the influence of the façade orientation on the optimum value of WWR was investigated in [42], where it was demonstrated that the strongest effect concerns the overall energy demand but more weakly the $WWR_{opt}$ value; therefore, in the analysis described in this paper, every simulation was carried out setting the same WWR for all the external walls of the building, regardless their orientation. This fact also allows the building structure to comply with the symmetry rules which are a typical feature of the reference building [48].

Furthermore, because of the fact that the optimal WWR also seems to be independent from the building geometry and only lightly influenced by the system efficiency [42], all the studied cases refer to the same geometrical configurations and the same HVAC system.

On the contrary, the insulation features of the façade were varied and the analysis was carried out in different climatic conditions in order to analyze the influence of these factors on the $WWR_{opt}$. Specifically, three types of envelope structures and 12 weather conditions were considered, corresponding to 12 Italian cities; they are described in the following paragraphs.

In addition, the effect of the luminaries features was also investigated, so that simulations were carried out in correspondence of different values of installed electric lighting power.

Finally, the influence of a switchable shading device was also examined and comfort aspects discussed.

To sum up, 518 configurations were simulated and analyzed.

### *2.1 The Weather Conditions.*

Italian peninsula is characterized by a variety of climate systems. According to the Köppen climate classification [55], they span from a relatively cool mid-latitude version of the continental climate, Dfa, typical of inland northern areas of Italy, to a Mediterranean climate profile, Csa, typical of coastal and Southern areas.

The sites selected to perform the simulations have climate conditions which are representative of this variety and, hence, allow a reliable appraisal of the effect of the weather variability on the energy efficiency of the building envelope.

Twelve cities were taken into account and their position on the Italian peninsula is portrayed in Figure 3; their geographical coordinates are reported in Table 1 together with the parameters describing the climate conditions: Heating Degree Day (18°C baseline),HDD, Cooling Degree Day (18°C baseline), CDD, and Climatic Vector, $V_c$ [56,57].

The latter parameter has been recently used to classify the Italian territory from the point of view of the summer climate conditions [57] and takes into account different climatic variables (absolute humidity, solar radiation, air temperature). The higher its value, the more severe the summer weather conditions are.

The climatic conditions of the selected cities are also depicted in Figure 4 reporting CDD and HDD versus $V_c$, and in Figure 5, where the annual solar radiation on the horizontal plane is also portrayed.

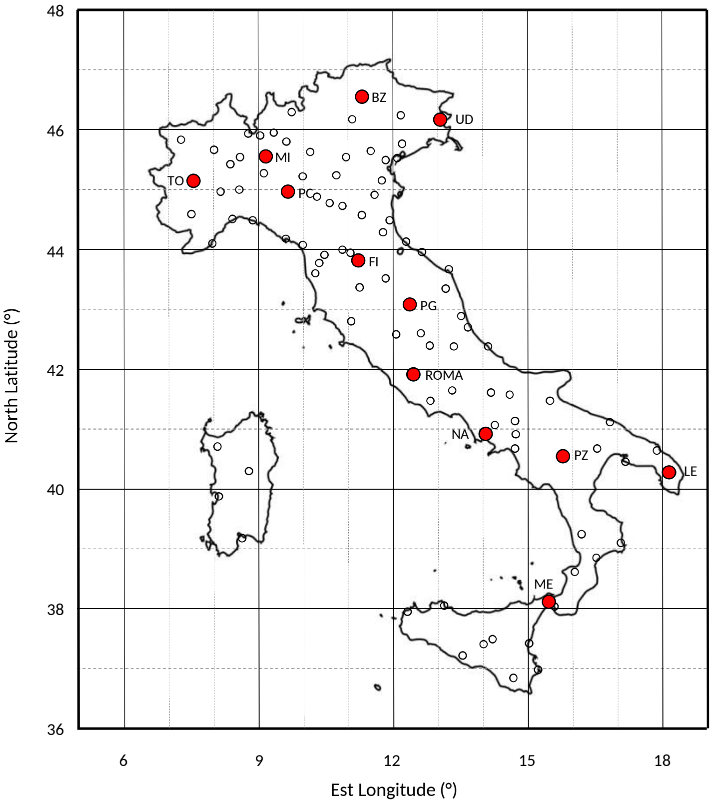



**Figure 3. Geographic Coordinates of Italian chief towns an of the selected cities .**

**Table 1. Geographical coordinates and climatic characteristics of the selected cities.**

| **Cities** | **ID** | **Latitude (°)** | **Longitude (°)** | **Altitude (m)** | **HDD (°C day) Baseline:18°C** | **CDD (°C day) Baseline:18°C** | **Annual Global Solar Radiation on the horizontal plane (kWh/m²)** | **Climatic Vector $V_c$** [56,57] | **Köppen climate classification** [55] | **ASHRAE Standard 196-2006 Climate Zone** [58,59] |
|---|---|---|---|---|---|---|---|---|---|---|
| Messina | ME | 38° 12’ | 15° 33’ | 59 | 881 | 837 | 1384 | 0.507 | Cfa | 3A |
| Lecce | LE | 40° 13’ | 18° 8’ | 48 | 1294 | 630 | 1333 | 0.452 | Csa | 3C |
| Naples | NA | 40° 50’ | 14° 18’ | 72 | 1446 | 539 | 1470 | 0.516 | Cfa | 3C |
| Rome | RM | 41° 47’ | 12° 34’ | 20 | 1558 | 575 | 1279 | 0.408 | Cfa | 3C |
| Florence | FI | 43° 47’ | 11° 11’ | 38 | 1901 | 528 | 1142 | 0.313 | Cfa | 3C |
| Perugia | PG | 43° 4’ | 12° 30’ | 213 | 2235 | 366 | 1256 | 0.163 | Dfa | 4A |
| Udine | UD | 46° 1’ | 13° 10’ | 92 | 2326 | 399 | 1035 | 0.230 | Dfa | 4A |
| Milan | MI | 45° 25’ | 9° 16’ | 103 | 2454 | 414 | 1071 | 0.312 | Dfa | 4A |
| Piacenza | PC | 44° 55’ | 9° 43’ | 134 | 2609 | 372 | 1077 | 0.167 | Dfa | 4A |
| Potenza | PZ | 40° 37’ | 15° 48’ | 843 | 2690 | 254 | 1267 | 0.090 | Cfb | 4A |
| Turin | TO | 45° 10’ | 7° 39’ | 282 | 2842 | 287 | 1102 | 0.185 | Dfb | 4A |
| Bolzano | BZ | 46° 28’ | 11° 19’ | 241 | 2913 | 254 | 1064 | 0.176 | Dfb | 4A |

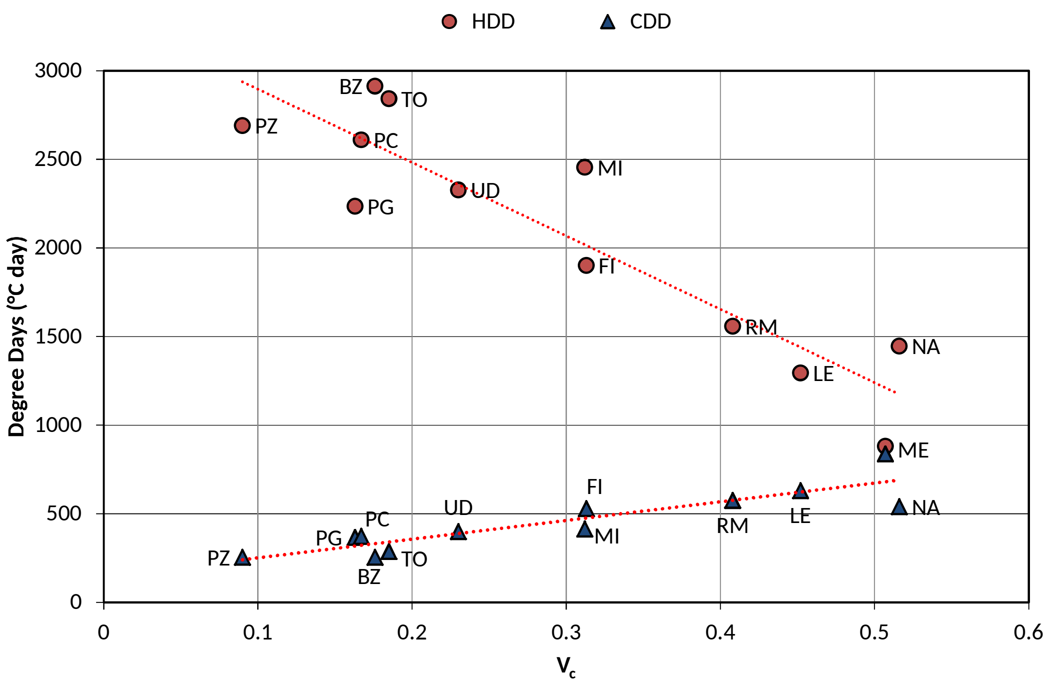



**Figure 4. Weather Conditions of the selected cities.**

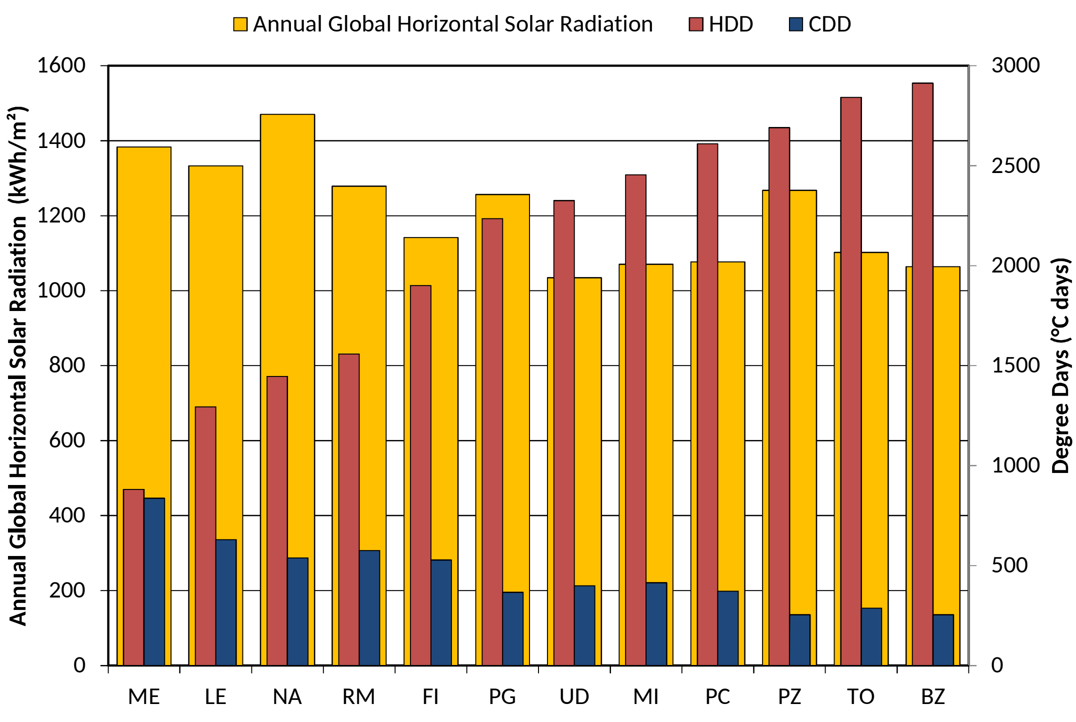



**Figure 5. Global Horizontal solar radiation, HDD and CDD for the selected sites.**

### *2.2 The building specifications*

Three building typologies were considered. They are indicated with the strings B1, B2 and B3 respectively, have the same geometric configuration (Figure 6) and differ only for the thermal –physical properties of the envelope structures. Specifically, B1 indicates the less insulated building, whereas B2 and B3 designate the edifices with enhanced insulation features and which differ from each other for the value of the window solar transmittance.

The three edifices refer to the medium size office building which has been singled out as the Italian reference building [48]. It has a covered area of 2400 m$^2$ and 5 floors above the ground. With regard to the interior plan layout, the typical floor consists of a central core (Figure 7), where stairs, elevators and service areas are located, and border rooms used as offices.

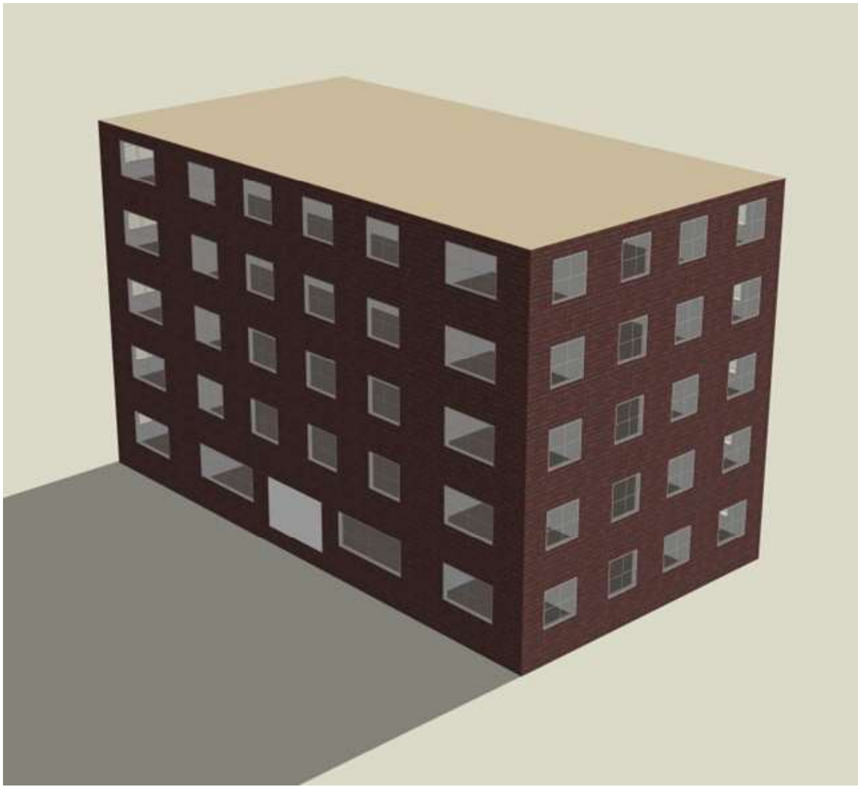


**Figure 6. Configuration of Building B1, B2 and B3.**

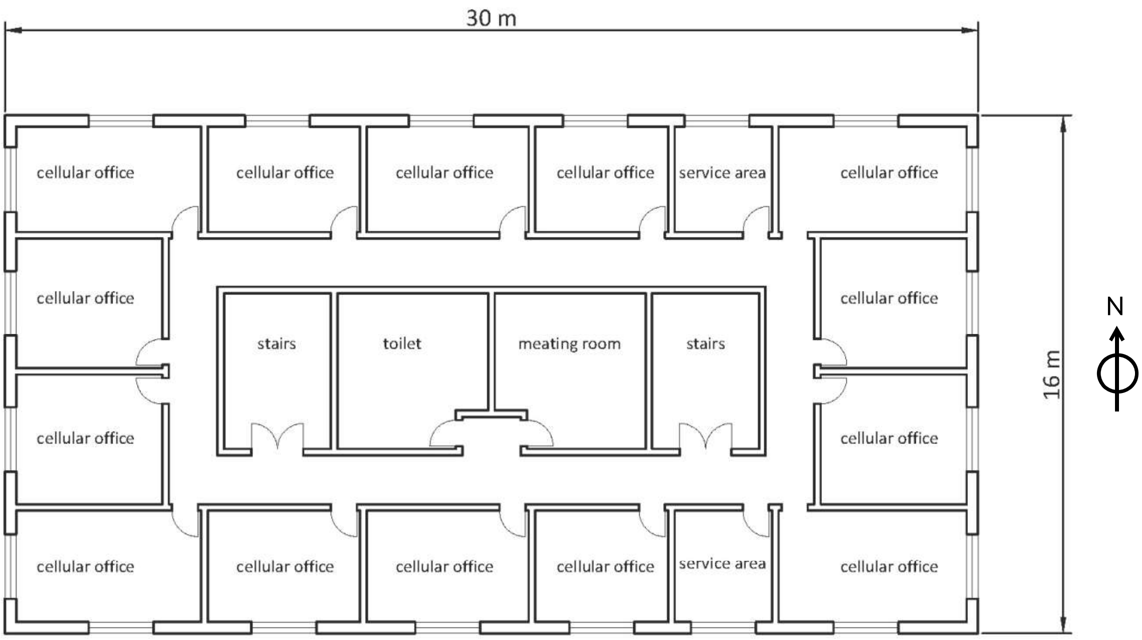



**Figure 7. Plan view of the typical floor of Building B1, B2 and B3.**

The thermal – physical features of the opaque and transparent components of the envelope are reported in Table 2 and Table 3 respectively [48].

**Table 2. Thermo-physical features of the opaque components of the envelope of the buildings B1, B2 and B3.**

| Building type | Component type | Thickness (m) | Thermal Trasmittance ($W/m^2K$) | Aerial Density ($kg/m^2$) | Aerial heat capacity ($kJ/m^2K$) |
|---|---|---|---|---|---|
| B1 | Wall | 0.254 | 0.760 | 275.26 | 49.49 |
| | Flat roof | 0.380 | 0.295 | 431.25 | 57.31 |
| | Slab above ground | 0.421 | 0.516 | 627.92 | 35.84 |
| B2 - B3 | Wall | 0.298 | 0.340 | 252.64 | 35.42 |
| | Flat roof | 0.380 | 0.295 | 431.25 | 57.31 |
| | Slab above ground | 0.495 | 0.300 | 667.64 | 36.38 |

**Table 3. Thermo-physical features of the transparent components of the envelope of the buildings B1, B2 and B3.**

| Building type | Thermal Trasmittance ($W/m^2K$) | Solar Heat gain Coefficient (dimensionless) | Visible transmittance (dimensionless) |
|---|---|---|---|
| B1 | 3.200 | 0.762 | 0.812 |
| B2 | 1.870 | 0.634 | 0.721 |
| B3 | 1.870 | 0.400 | 0.700 |

In regard to the use of the building, indoor thermal comfort, occupancy, lighting and equipment schedules were defined with reference to Italian and European Standards [60–63] as considered representative of the daily usage of the building in Italy. All the mentioned data are reported in Table 4 and Table 5, whereas the use patterns are depicted in Figure 8.

The lighting system is turned on when daylight illuminance decreases below a fixed value which was set to 500 lux for office rooms and to 200 lux for isles and stairwells (Table 5). Furthermore, with reference to the installed electric power, four configurations (L1, L2, L3, L4) were considered (Table 4).

In all the analyzed buildings the primary systems for heating and cooling consist respectively of a gas boiler and an air cooled chiller, the terminals are four pipe fan coil units [48].

**Table 4. Features of systems and environment occupancy data in buildings B1, B2 and B3.**

| Environment type | Internal gains ($W/m^2$) | Air change ($l/s\ m^2$) | Installed Electric Power ($W/m^2$) | | | |
|---|---|---|---|---|---|---|
| | | | L1 | L2 | L3 | L4 |
| Office Room | 10 | 0.6 | 10 | 15 | 20 | 25 |
| Stairwells and aisles | 3 | 0.3 | 4 | 6 | 8 | 10 |
| Overall Average | 8.6 | 0.5 | 8.8 | 13.2 | 17.6 | 22 |

**Table 5. System set-points and triggers.**

| Environment type | HVAC system | | Lighting system |
|---|---|---|---|
| | Heating set point (°C) | Cooling set point (°C) | Trigger (lux) |
| Office Room | 20 | 26 | 500 |
| Stairwells and aisles | | | 200 |

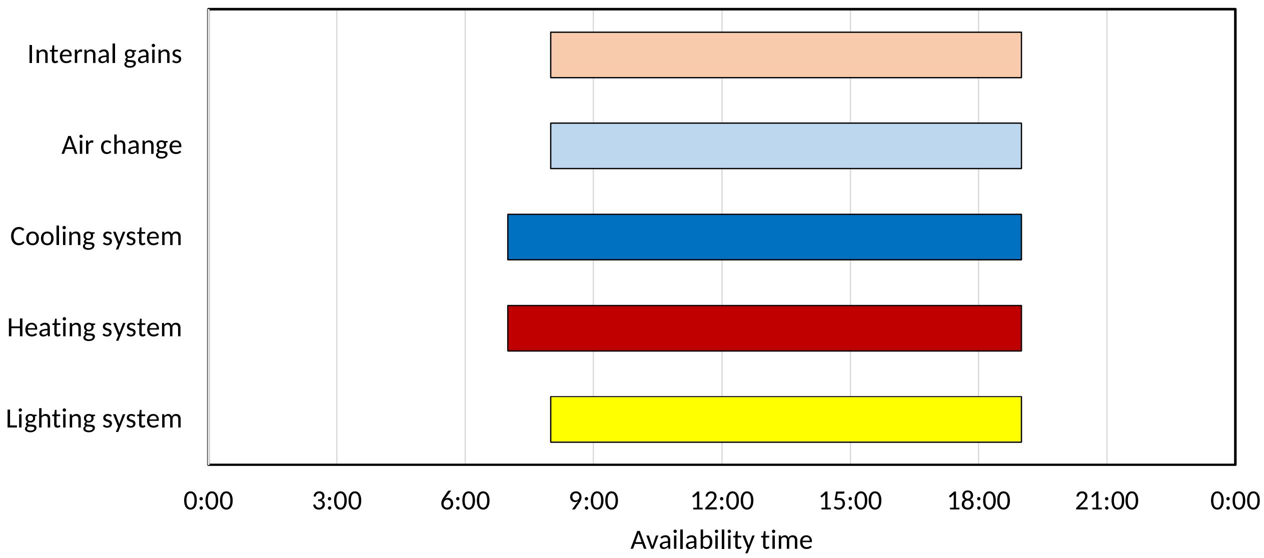



**Figure 8. Use patterns for every week day from Monday to Friday of the buildings B1, B2 and B3.**

# 3 Results

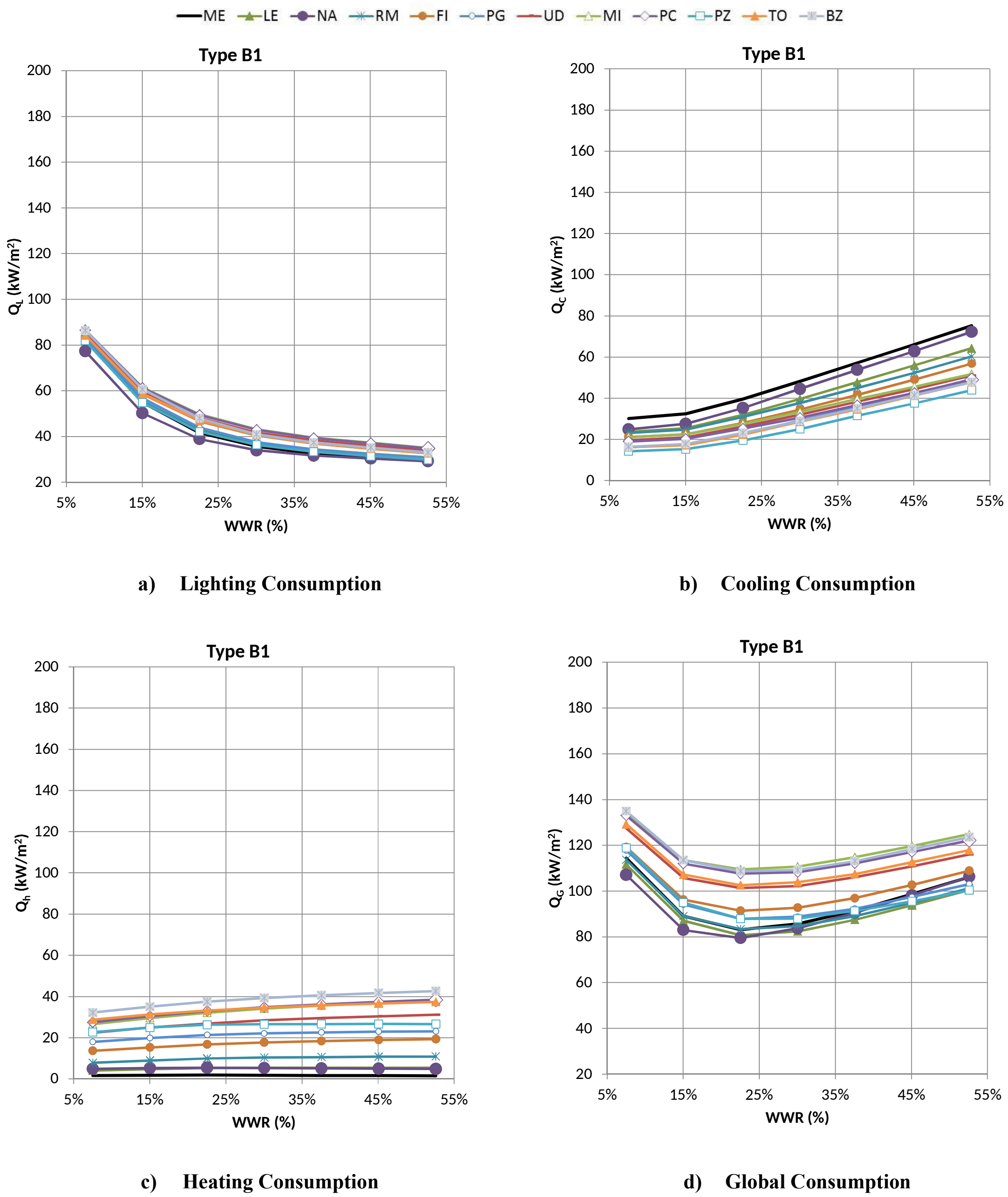
The analysis was carried out considering different points of view. Firstly, the effect of the weather conditions were analyzed for all the building types.

Secondly, two extreme weather conditions were considered (corresponding to Messina and Bolzano site) and the installed electric power of the lighting system was varied with a view to analyzing its influence on $WWR_{opt}$. In regard to this aspect four configurations were considered as specified in the following paragraphs.

Finally, the effect of a switchable shading device was investigated and discussions on comfort issues were carried out.

## *3.1 The effect of the climate conditions*

Figure 9, Figure 10 and Figure 11 depict the trend of the primary energy consumption versus the window to façade ratio, WWR, for the three building configurations respectively, when the lighting system is arranged according to configuration L3. The reported results, moreover, refer to all the considered climate conditions.



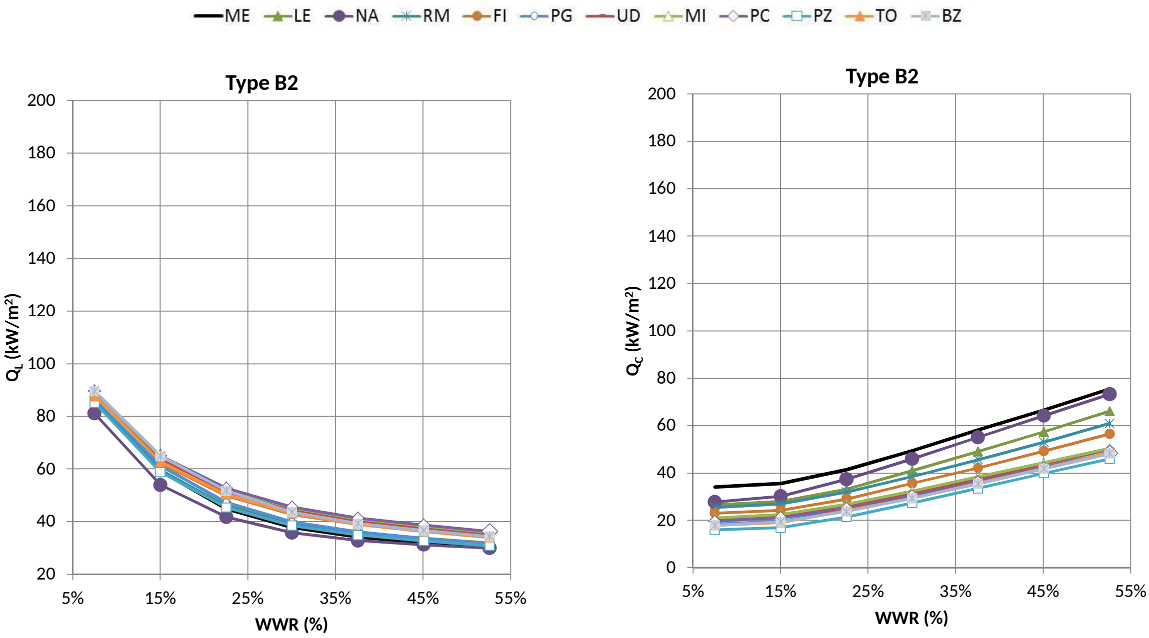

a) Lighting Consumption

b) Cooling Consumption

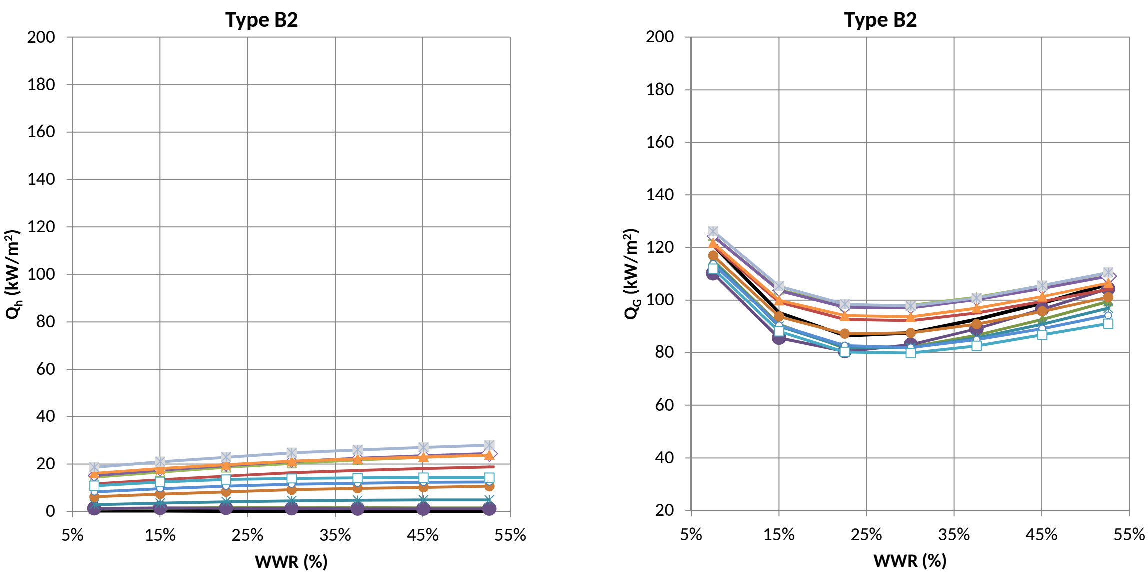
c) Heating Consumption

d) Global Consumption

**Figure 9. Primary Energy Consumption versus WWR - Building B1– Lighting system configuration: L3.**

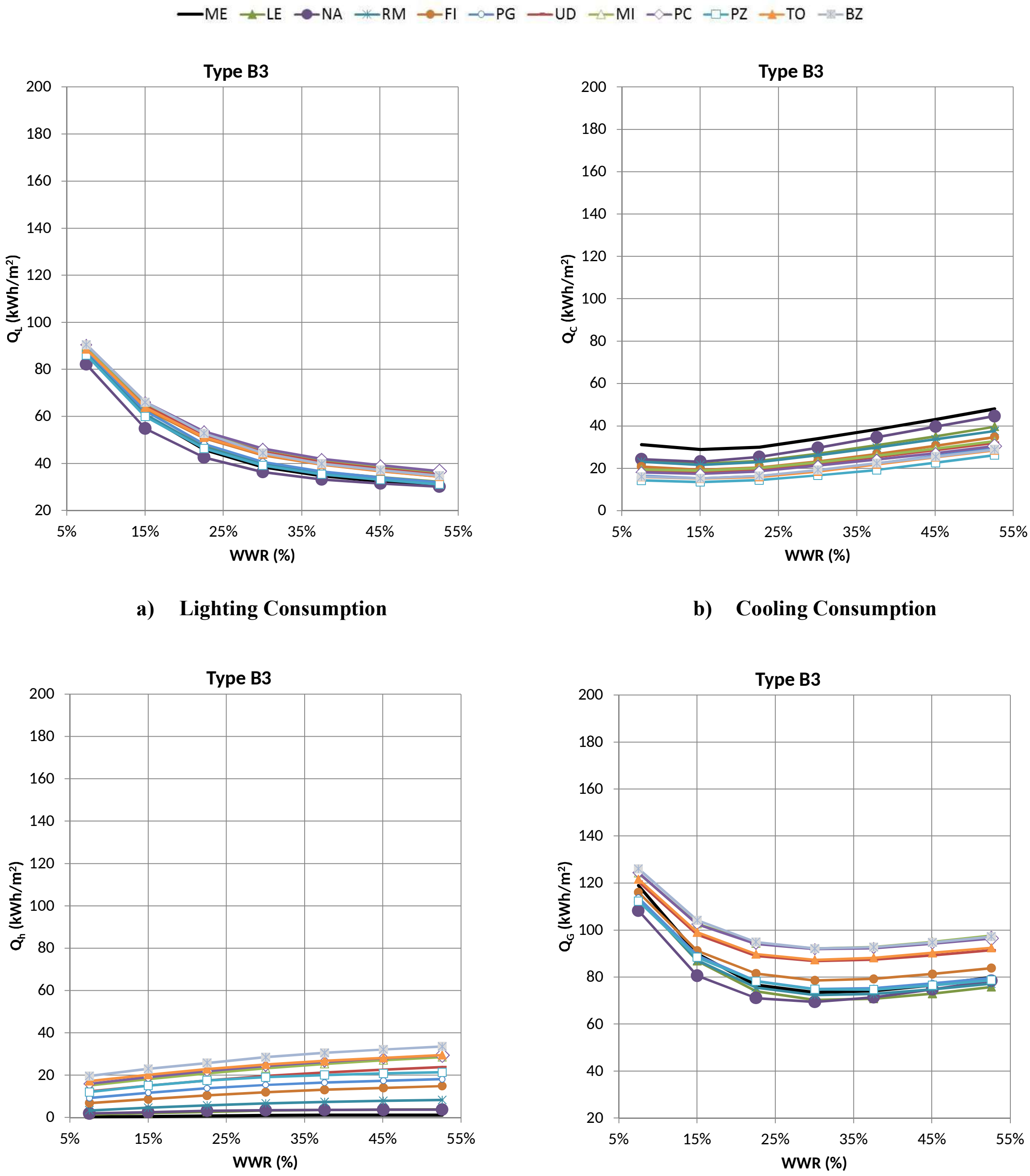



**a) Lighting Consumption** **b) Cooling Consumption**




**c) Heating Consumption** **d) Global Consumption**

**Figure 10. Primary Energy Consumption versus WWR - Building B2– Lighting system configuration: L3.**




a) Lighting Consumption

b) Cooling Consumption

c) Heating Consumption

d) Global Consumption

**Figure 11. Primary Energy Consumption versus WWR - Building B3 – Lighting system configuration: L3.**

The optimum value of WWR, for every building typology, is reported in Table 6 and Figure 12. Being the result of the opposite effects of lighting and air-conditioning demand, it slightly varies with weather conditions (the standard deviation is always lower than 1.5%) owing to the fact that in colder climate the reduction of cooling needs is compensated by an increase of the heating ones.

**Table 6. Optimum value of the ratio WWR for buildings B1, B2 and B3 - Lighting system configuration: L3.**

| city | Type B1 | Type B2 | Type B3 |
|---|---|---|---|
| **ME** | 22.9% | 25.0% | 30.9% |
| **LE** | 23.7% | 25.7% | 31.9% |
| **NA** | 20.9% | 22.5% | 28.7% |
| **RM** | 23.7% | 26.1% | 32.0% |
| **FI** | 23.3% | 25.4% | 32.0% |
| **PG** | 24.6% | 26.8% | 32.4% |
| **UD** | 23.5% | 26.6% | 31.3% |
| **MI** | 22.9% | 25.6% | 31.4% |
| **PC** | 23.7% | 26.1% | 31.9% |
| **PZ** | 25.6% | 26.8% | 33.8% |
| **TO** | 23.3% | 27.2% | 31.0% |
| **BZ** | 24.3% | 27.1% | 31.9% |
| **Mean** | 23.5% | 25.9% | 31.6% |
| **Standard Deviation** | 1.1% | 1.3% | 1.2% |

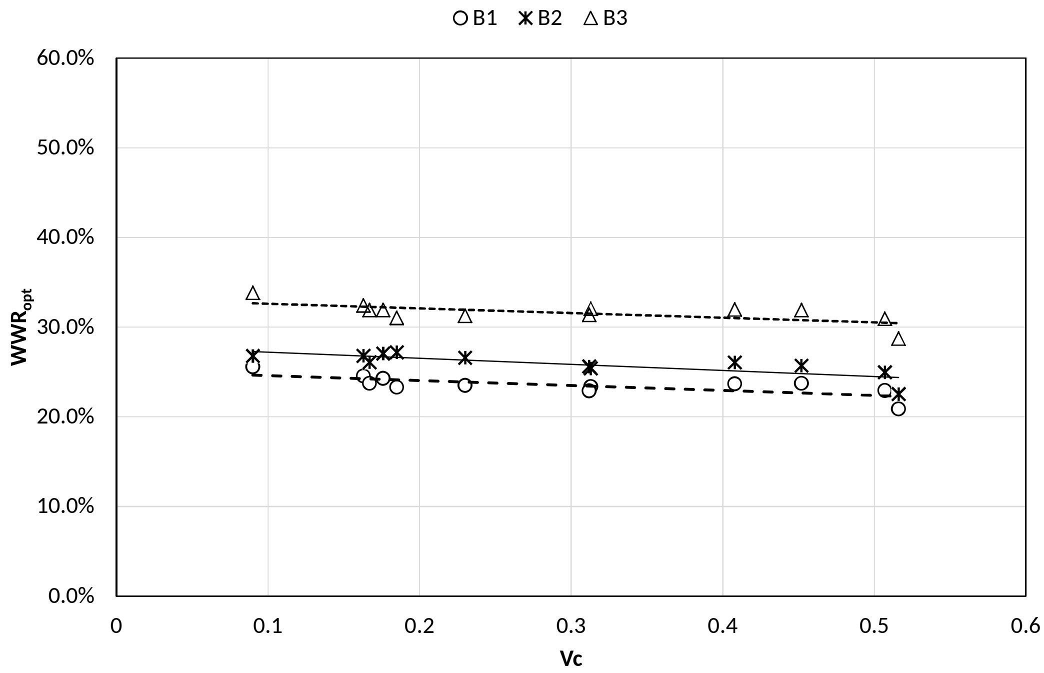



**Figure 12. Optimum value of the ratio WWR for Building B1, B2 and B3 - Lighting system configuration: L3.**

In short, since the standard deviation values are 1.1% for building B1, 1.3% for building B2, 1.2% for building B3 (Table 6), it can be inferred that the climate region has a poor influence on the optimum value of WWR for all the examined configurations.

Therefore, the average value of $WWR_{opt}$ can be used as a reference, regardless the climate. It is equal to 23.5% for building B1, to 25.9% for building B2, to 31.6% for building B3.

### *3.2 The effect of the thermal insulation of the envelope structures*

The optimum value of WWR seems marginally influenced by an improvement of the envelope thermal insulation; as a matter of fact, comparing the results inferred for the two building B1 and B2, whose envelope structures are characterized by different thermal features (Table 2 and Table 3), the average value of $WWR_{opt}$ slightly increases from 23.5% to 25.9%.

This phenomenon may be due to the fact that, as a general rule, the improvement of the insulation properties of the envelope, albeit lowering the heat exchanges between indoor and outdoor environments, only slightly enhances the weight of the lighting demand on the overall consumption.

With a view to clarify this aspect, Figure 13 depicts the trends of the primary energy consumption as a function of WWR, for the two extreme climatic conditions of Messina and Bolzano.

It can be inferred that in climates characterized by hot summer and mild winter (Messina), the slight decrease of the heating demand, due to an improvement of the envelope insulation features, is compensated by an increase in the cooling one, whereas the lighting energy demand feebly rises because of the lower values of the visible transmittance (Table 3) of the windows. As a consequence, a more insulated envelope lightly enhances the weight of the lighting demand and, hence, it allows a slight increase of the optimum value of WWR (from 23% to 25% - Figure 13), even though, on balance, the overall energy demand appreciably rises.

On the other hand, in colder climates (i.e. Bolzano), the increase of the envelope thermal insulation significantly affects the heating consumption (Figure 13), reducing it, whereas the cooling and lighting ones are less influenced. As a result, a more insulated envelope allows a slight enhancement of the window sizes if energy consumption is to be kept within minimum level. In this case $WWR_{opt}$ varies from 24% for building B1 to 27% for building B2 (Figure 13).

On the contrary, in both climate conditions, the improvement of the window optical features (building B3), causes a substantial reduction of the cooling consumption, so that higher value of $WWR_{opt}$ are allowed (31% at Messina, 32% at Bolzano- Figure 13).

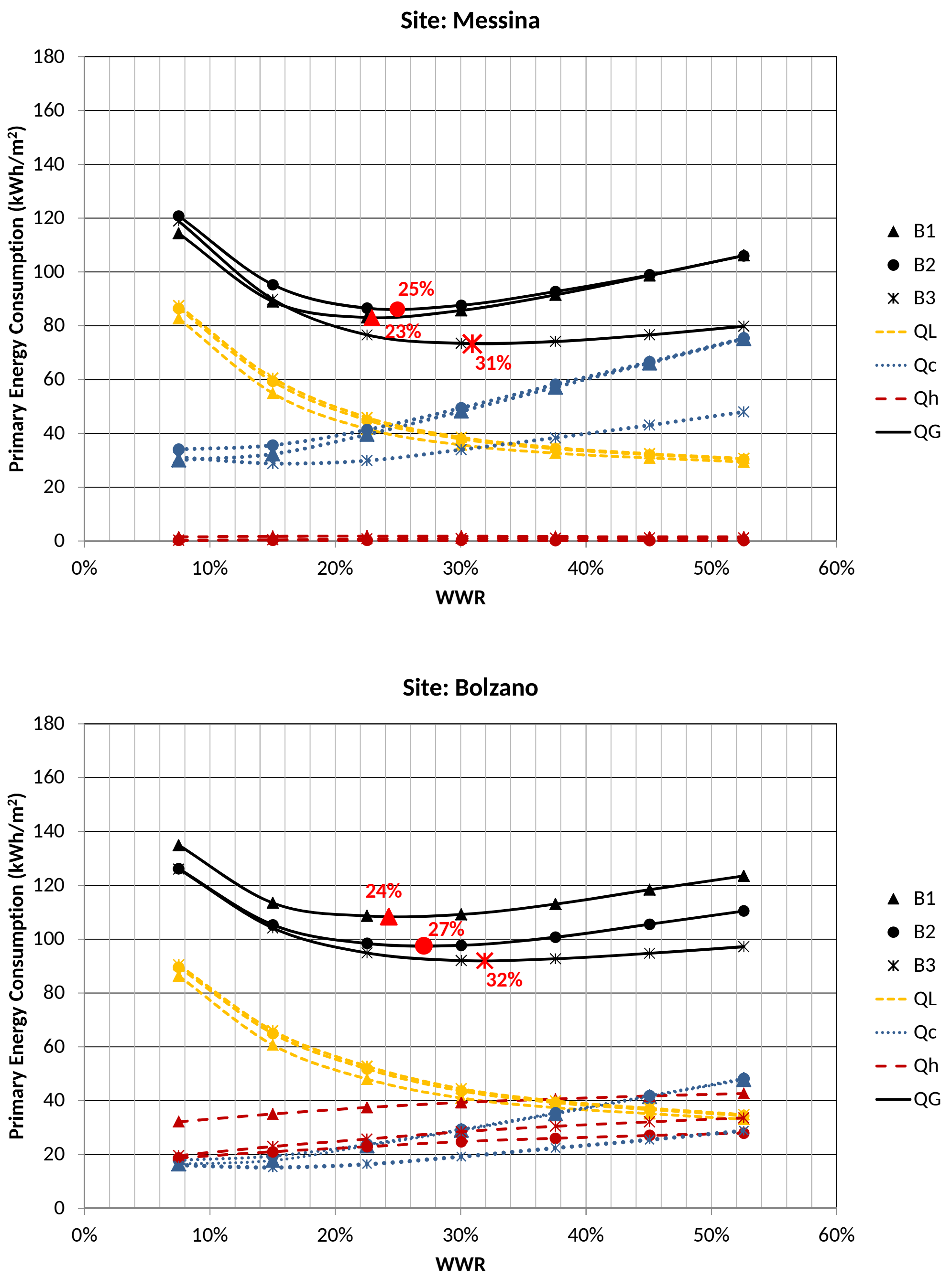



**Figure 13. Primary Energy Consumption versus WWR Lighting system configuration: L3.**

### *3.3 The effect of the installed lighting electric power*

The analysis formerly reported refers to a lighting system consisting of luminaries with fluorescent lightings and an installed power, $P_L$, of 8 W/m$^2$ in aisles and stairwells and 20 W/m$^2$ in office rooms (configuration L3 - Table 4) which, with an illuminance set-point of

500 lux, corresponds to the second quality class defined in [61] as allowing a good fulfilment of requirements.

The visible fraction of the electric input, as well as the fractions contributing to internal loads, are set as specified in [64].

In order to better understand the influence of the installed power on the optimal size of the glazed surfaces, other simulations were carried out changing its value. The analysis, in this case, was referred to the two extreme climatic conditions of Messina and Bolzano.

To sum up, four configurations of the lighting system were considered as specified in Table 4, which reports the electric power installed in both office rooms and service areas and the correspondent averaged value ($P_L$ – overall average in Table 4) calculated as a mean weighted by means of the floor areas of each indoor environment.

The results of this analysis are reported in Figure 14, Figure 15, Figure 16, Figure 17.

As expected, the increase of the installed power causes the rise of the lighting energy consumption at both the considered sites (Figure 14). Furthermore, the lighting consumption is higher for the more insulated buildings (i.e. B2 and B3), owing to the fact that windows with lower thermal transmittance also have a lower visible transmittance (Table 3).

As far as the cooling demand is concerned, Figure 15 shows that it rises with $P_L$, because of the rise of the heat loads generated by the luminaries.

The enhancement of the heat gains also influences the heating consumption (Figure 16) which decreases when $P_L$ grows.

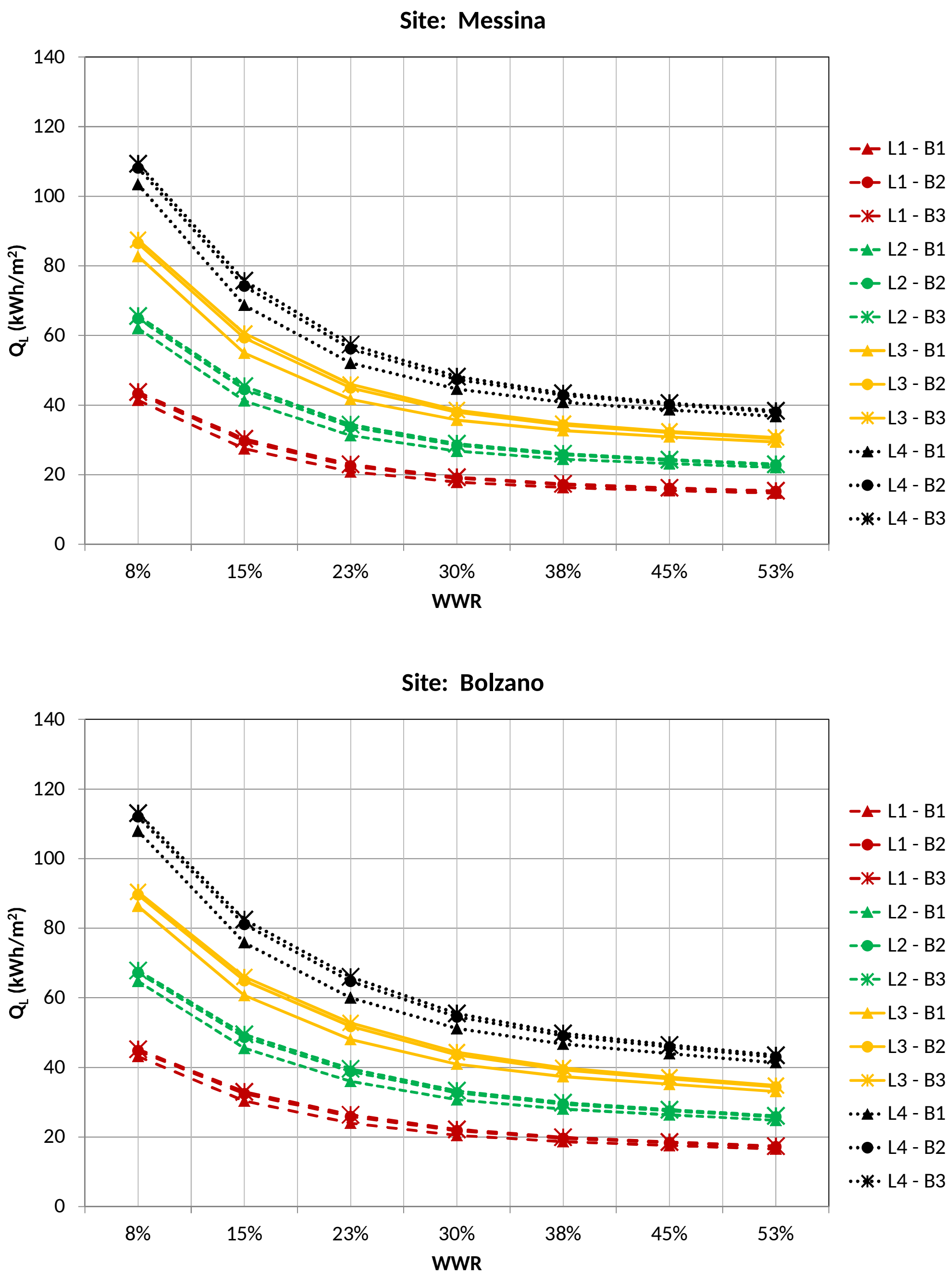
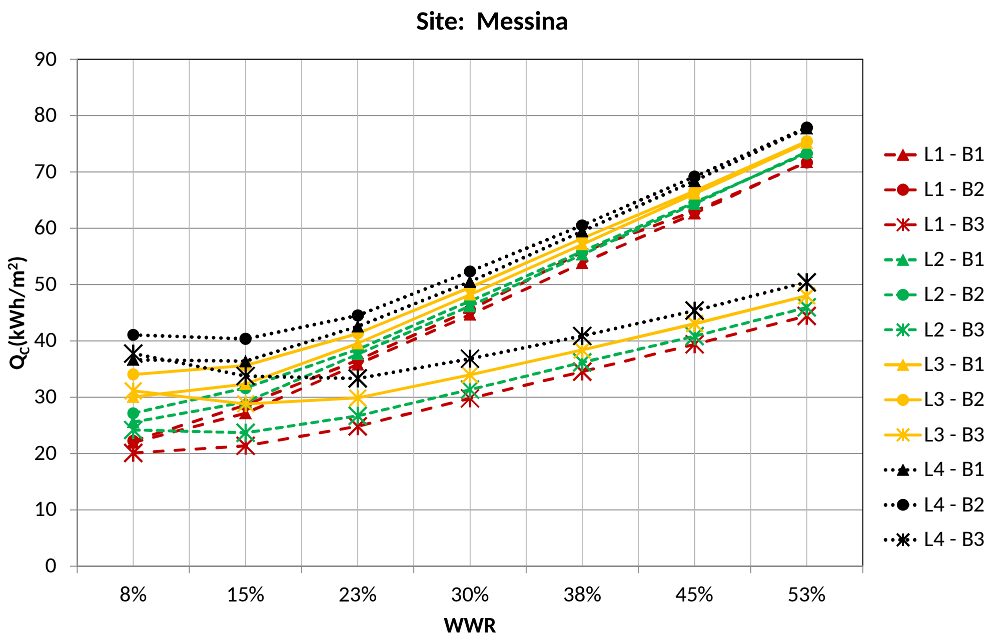



**Figure 14. Lighting Primary Energy Consumption versus WWR.**



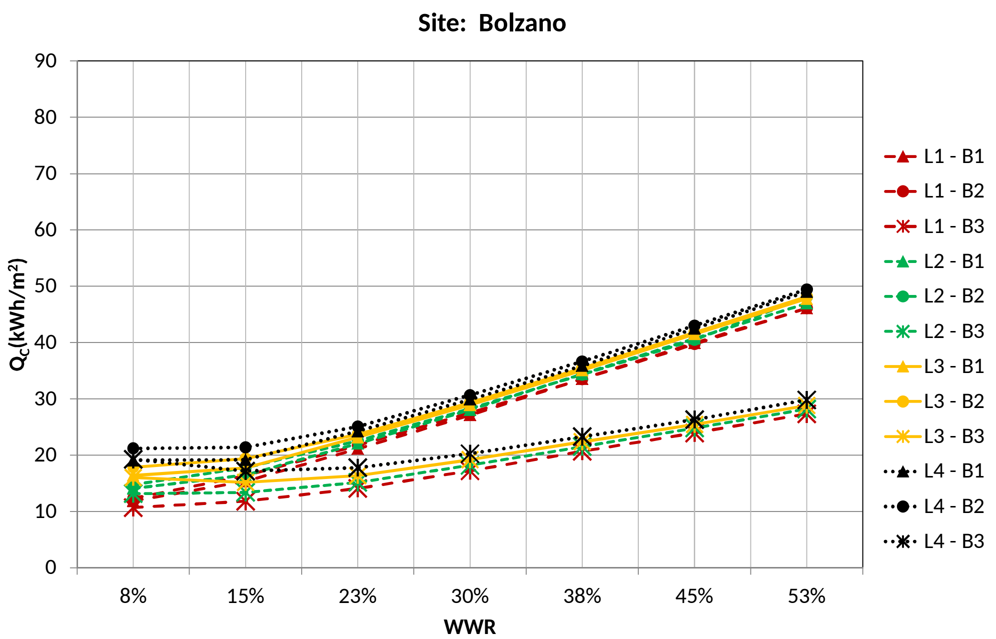




**Figure 15. Cooling Primary Energy Consumption versus WWR.**

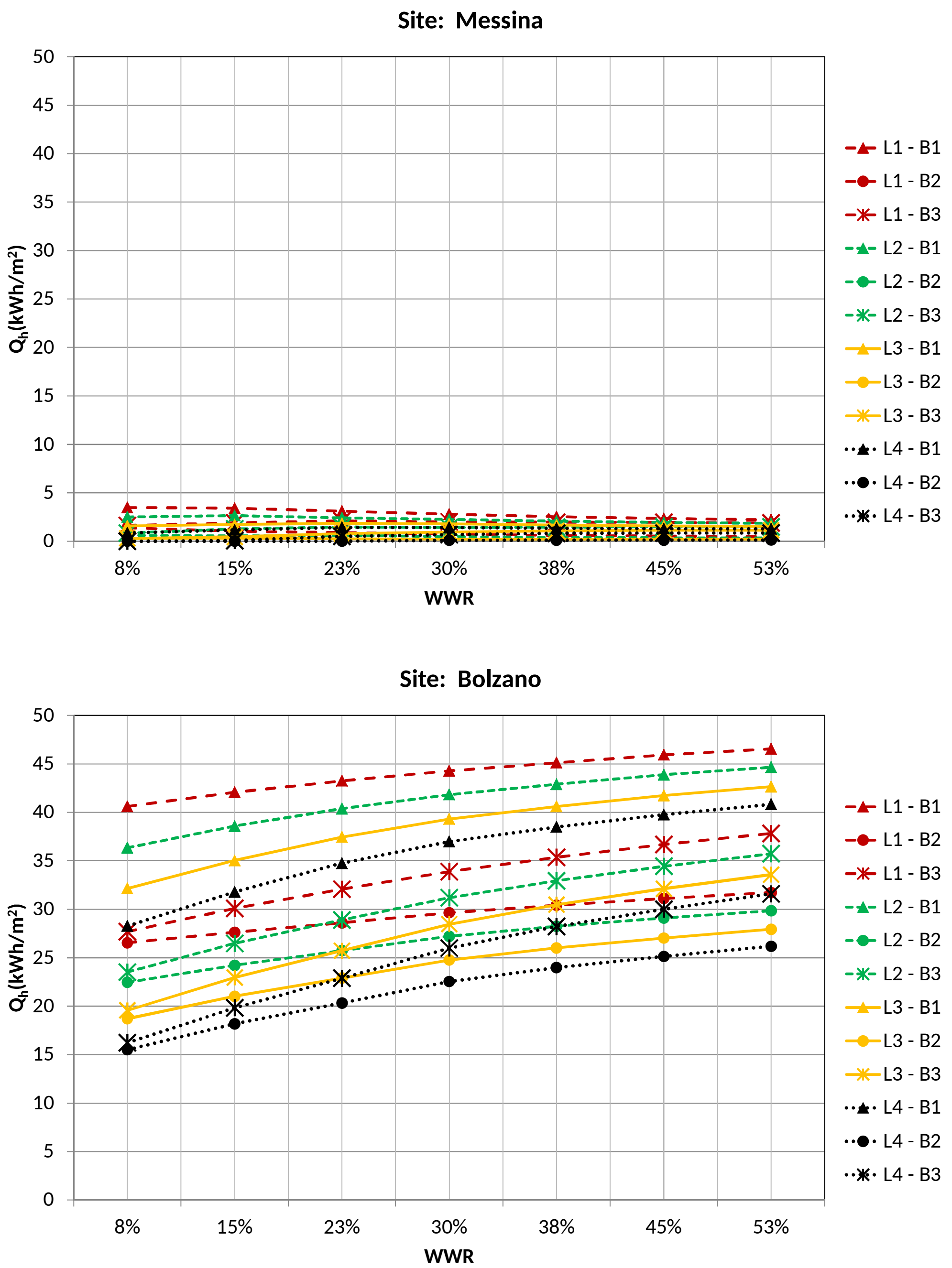
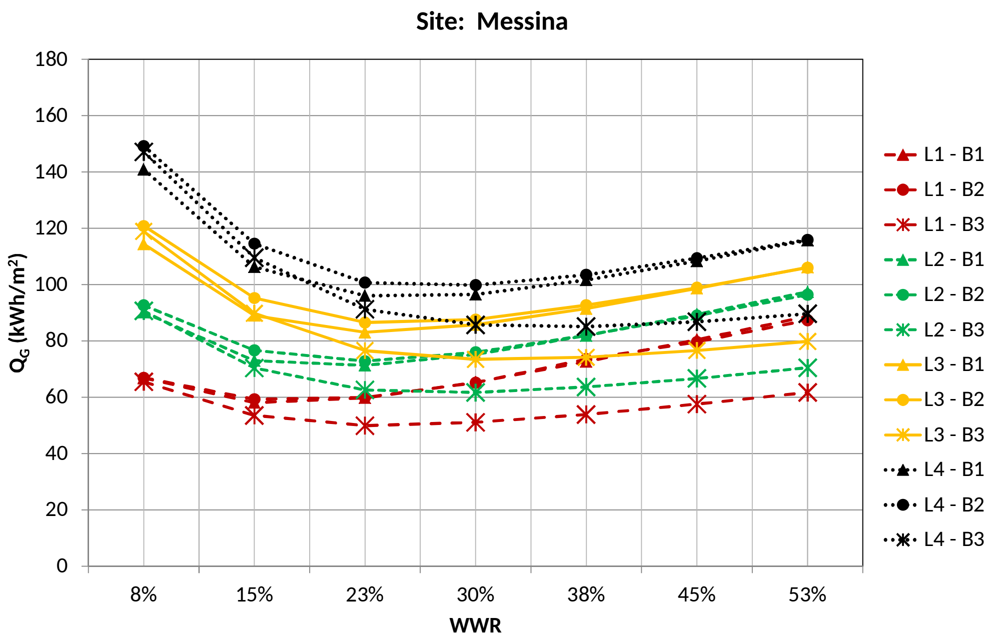



**Figure 16. Heating Primary Energy Consumption versus WWR.**

Obviously, the global energy consumption (Figure 17) is affected by these phenomena: when $P_L$ is raised, the enhancement of the lighting and cooling energy consumption combines with the decrease of the heating one and, on balance, the building global energy needs rise.

In addition, it is also worth noting that (Figure 17) in colder climate (Bolzano), for buildings with large window size (WWR>23%), from an energy efficiency point of view, the improvement of the insulation features of the envelope may be more appropriate than a slight reduction of the installed lighting electric power.

As a matter of fact, in Bolzano, when WWR>23%, the enhancement of the thermal resistance of the façade components (from building B1 to Building B2) causes a decrease of $Q_G$ which is higher than the one resulted by reducing $P_L$ of about 4.4 W/m$^2$ (Figure 17), which, on average, is the variance between two subsequent lighting system configurations.



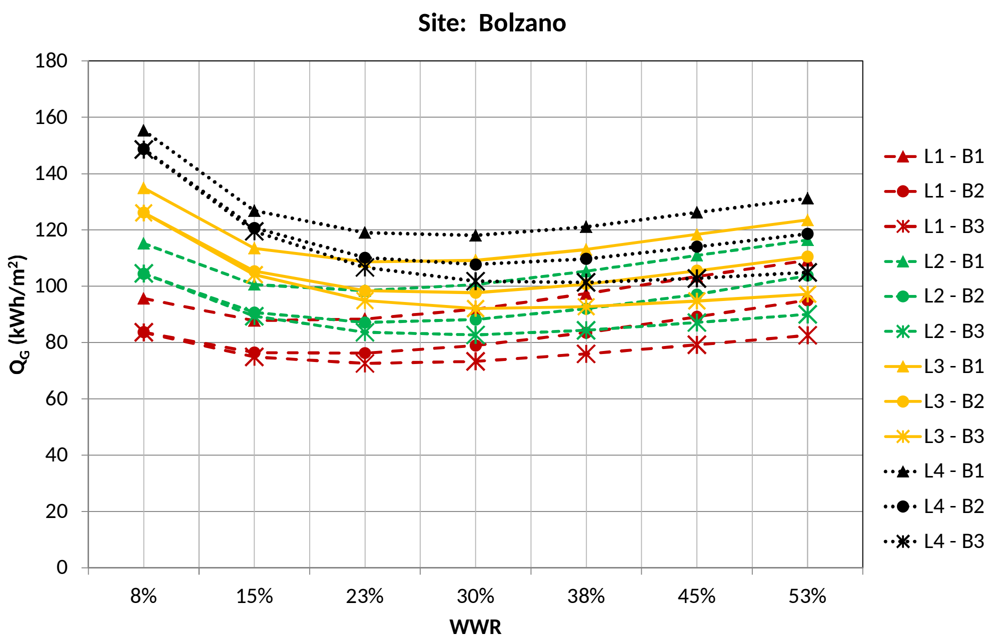




**Figure 17. Global Primary Energy Consumption versus WWR**

As regards the issue of the optimal window size, it can be inferred that, regardless the climate conditions, the enhancement of the installed electric power $P_L$ and the consequent rise of the lighting energy consumption, also cause the increase of $WWR_{opt}$ (Figure 18).

The rate of this increase is slightly higher when more energy efficient building envelope structures (building types B2 and B3) are involved.

Both these facts should be accurately taken into account during the building project phase, because they demonstrate the connection between the envelope design and the system sizing which, therefore, are to be considered as part of the same process.

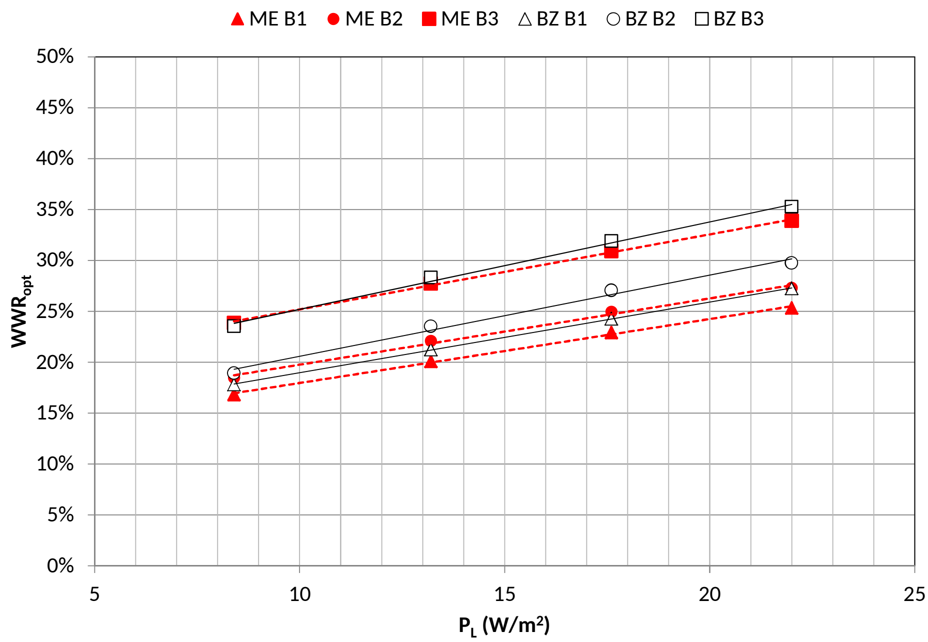



**Figure 18. Influence of installed lighting electric power $P_L$ on the optimum value of WWR.**

## *3.4 The effect of smart switchable shading devices*

The former analysis does not take into account the effect of shading devices which could be actually used to prevent the occurrence of glare issues in office rooms.

By and large, their presence both reduces the glare risk and improves visual comfort conditions, but alters the energy demand and might provoke an increase in the overall consumption. This phenomenon might make the presence of optimal sized windows partially ineffective.

In order to analyze this aspect, the windows of building B1 and B2 were equipped with electrochromic (EC) glazing. Building B3, whose envelope structures have the same thermal characteristics of building B2 and only differ for the optical features of the installed selective glass, was exploited as comparison case in this analysis.

The bleaching of the electrochromic glass was controlled on the basis of the daylight conditions. In this case the transmittance of the glazing is adjusted to meet the daylight illuminance set-point for the main photoelectric sensor used, in every room, to control electric lighting. This type of control assures that there is just enough daylight transmitted through windows with electrochromic shading to meet the daylighting requirements in a zone, and no more, thus reducing the cooling load and the glare risk. In former studies [65] this control type has demonstrated to be the most effective in preventing energy consumption growth. The daylight illuminance set-point was set to 500 lux in office rooms (Table 4) and the sensors were considered located at the center of each environment.

As regards the installed lighting electric power, $P_L$, the four configurations L1, L2, L3, L4 were considered.

Obviously, from the point of view of visual comfort, the analysis must be carried out at room level. Only on this scale it is possible to evaluate the quality of the visual indoor environment defined by the occupant.

The parameter used for visual comfort assessment is the daylight glare index DGI defined as [50,66,67]:

$$DGI = 10\log_{10} 0.48\sum_{i=1}^{n} \frac{L_{\omega_i}^{1.6} \times \Omega_i^{0.8}}{L_{b_i} + 0.07\omega_i^{0.5} L_{\omega_i}} \tag{6}$$

where:

$n$ is the number of windows;

$L_{\omega_i}$ is the average luminance of the window i as seen from the reference point (cd/m$^2$);

$\Omega_i$ is the solid angle subtended by the window i, modified to take direction of occupant view into account (sr);

$L_{b_i}$ is the luminance of the background area surrounding the window i (cd/m$^2$);

$\omega_i$ is the solid angle of the window i from the point of observation (sr).

An example of the results of this analysis, regarding the office room (Figure 19) located at the South-Est corner of the third floor of the studied buildings (Figure 7), is reported in Figure 20. It is referred to the sites of Messina and Bolzano, a window to façade surface ratio of 0.30 and depicts the percentage of time, *f*, during which the glare index DGI, for a seated Est facing subject located at the center of the room (position P1 in Figure 19), exceeds the maximum allowable value of 21 [68] for both cases of simple (NO EC) and electrochromic (EC) glazed windows.

The percentage of time *f* is referred to the period during which the office room is occupied, which spans from 8:00 to 19:00 of every week day from Monday to Friday, as specified by the following equation:

$$f = \frac{P(DGI > 21)}{P_{occ}}$$

where:

P(DGI>21) is the duration of the period of time during which the condition DGI>21 occurs during the simulated year;

$P_{occ}$= 2871 hours is the duration of the period of time during which the office room is occupied (from 8:00 to 19:00 of every week day from Monday to Friday) during the simulated year.

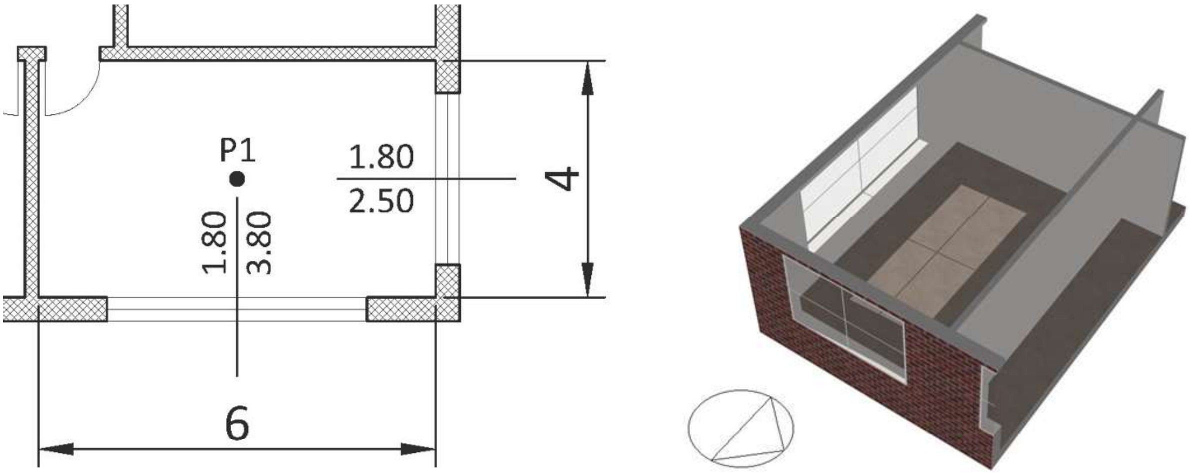



**Figure 19. Sketch of the office room located at the South-Est corner of the third floor of the studied buildings .**

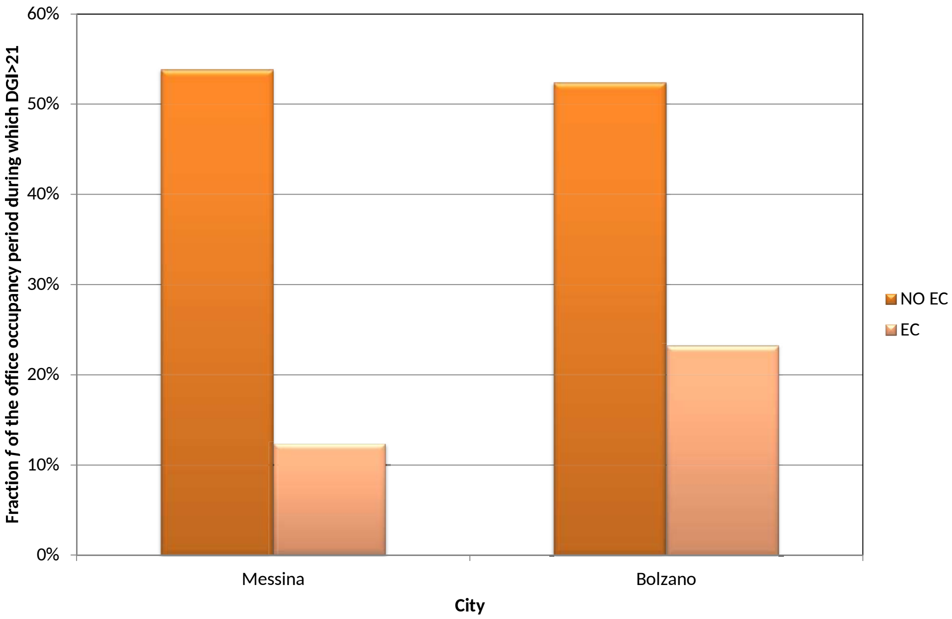
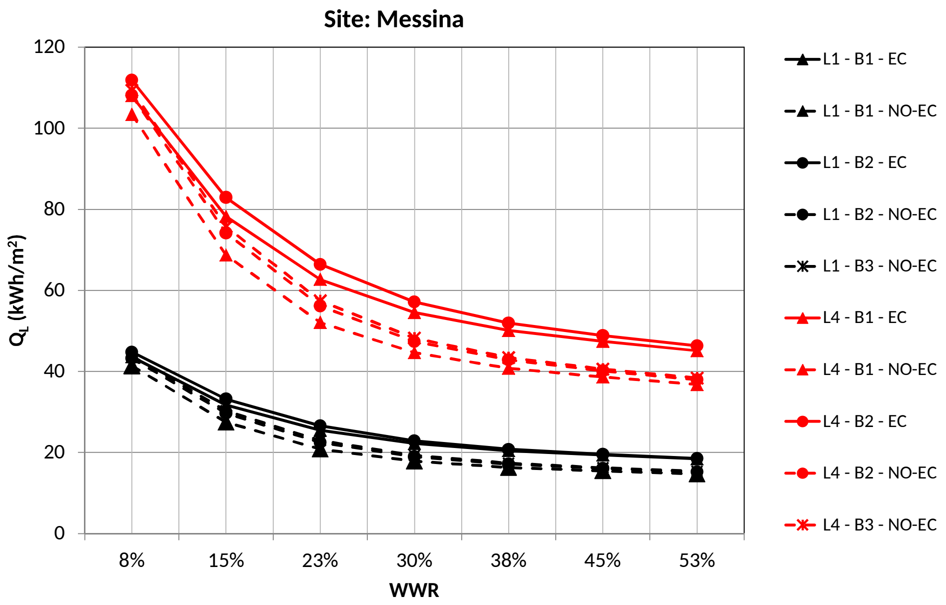



**Figure 20. Fraction of time during which DGI>21- Building B1 – WWR=30%.**

As expected, the shading device drastically reduces the discomfort period over the whole simulated year.

On the other hand, as far as energy consumption is concerned, the presence of the switchable shading device alters the building energy performance considerably. This circumstance is deducible from the graphs reported in Figure 21, 22, 23 and Figure 24 where the energy consumption for the two extreme cases corresponding to lighting system configurations L1 and L4 is depicted.

For both climate conditions, the presence of the shielded window reduces the solar radiation entering the indoor environment; as a consequence, the lighting demand rises (Figure 21) as well as the heating one (Figure 23), whereas the cooling consumption decreases (Figure 22) owing to the solar gain drop.



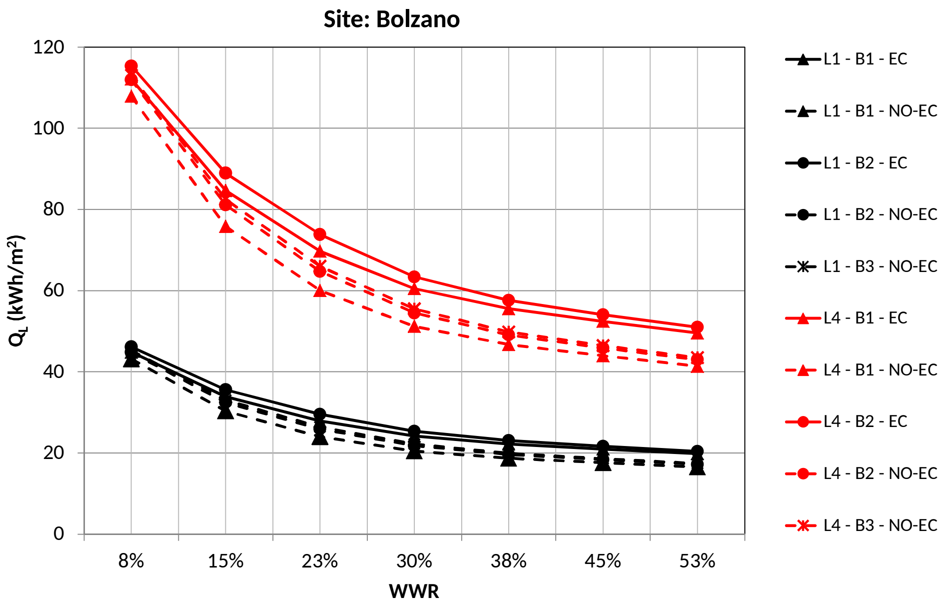
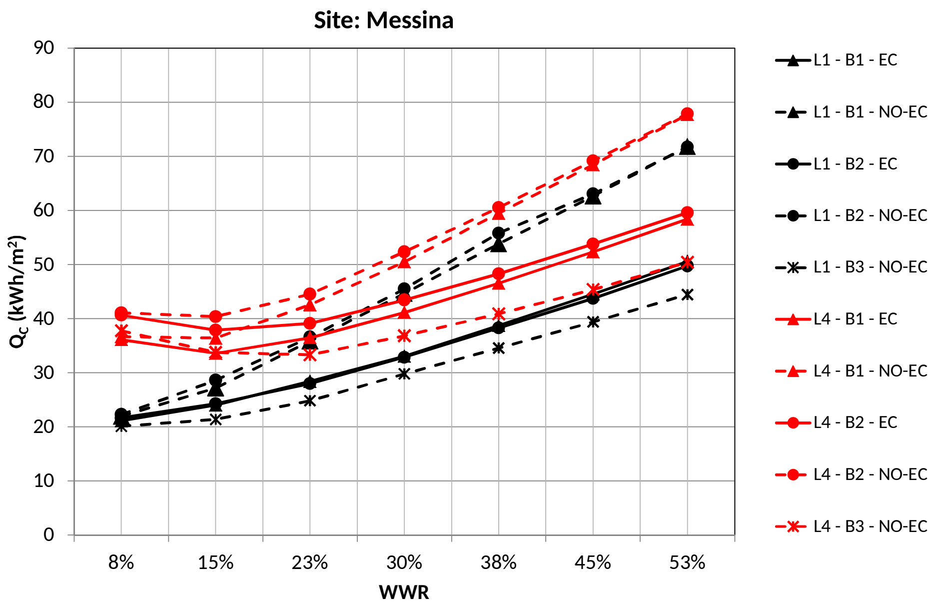




**Figure 21. Lighting Primary Energy Consumption versus WWR.**



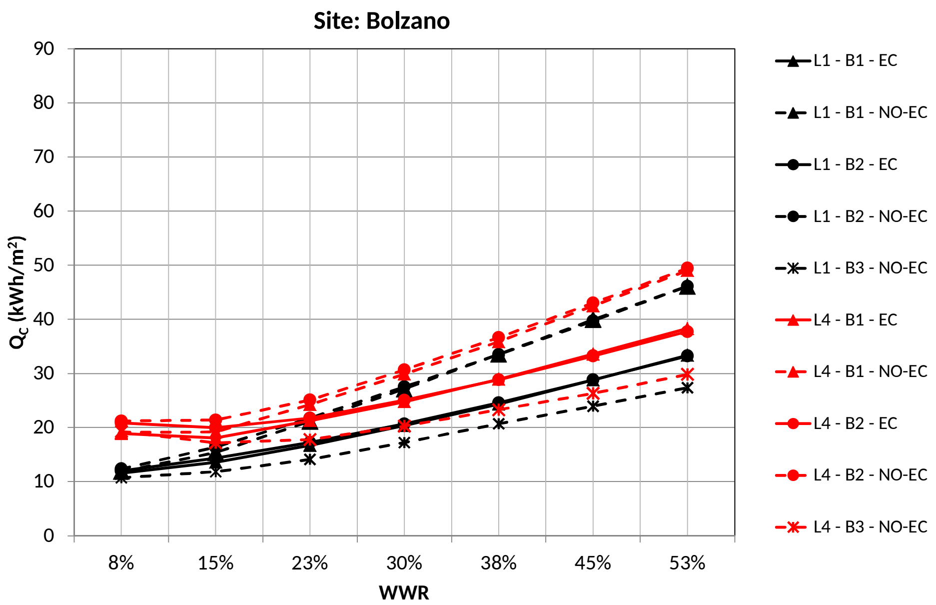




**Figure 22. Cooling Primary Energy Consumption versus WWR.**

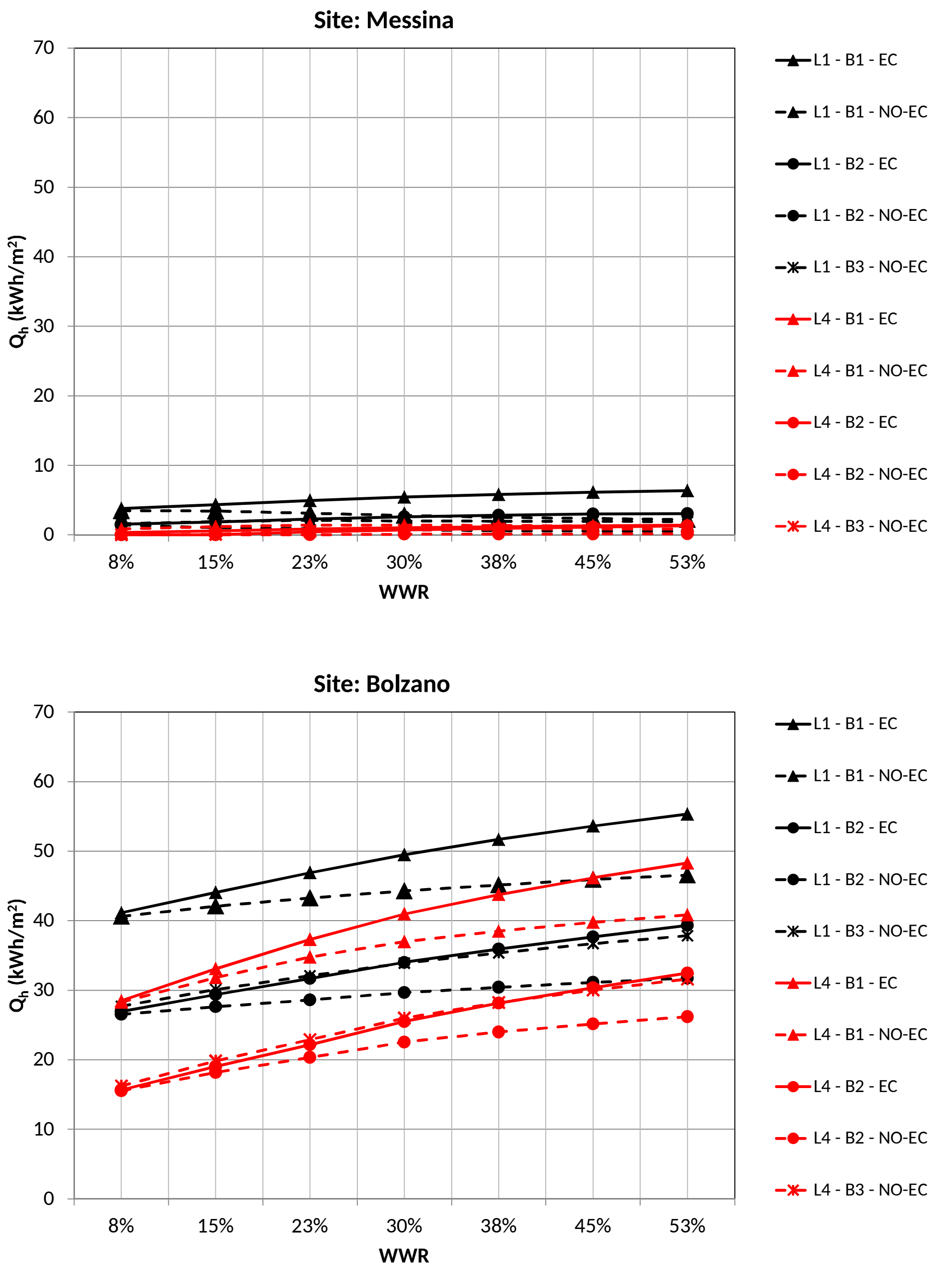



**Figure 23. Heating Primary Energy Consumption versus WWR.**

The effects of these phenomena on the global consumption $Q_G$ depends on the climate (Figure 24).

At Messina site, the shielded window affects the overall consumption $Q_G$ with different results depending on the value of WWR. For example, if L4 lighting system configuration is considered, the presence of shading device provokes a rise of the overall consumption when WWR<35%; but for WWR>35% it causes a reduction of $Q_G$, owing to a proper control of the solar gain. The same behavior occurs in correspondence of L1 configuration, but the discontinuity value of WWR changes to 23%.

Therefore, in warmer climates, also in substantial accordance with similar results reported in [43], when the glazed surface occupies more than a quarter of the façade surface, shading devices might become crucial for energy saving purposes and appear to be a measure more efficient than the improvement of the envelope insulation features.

At Bolzano site, on the contrary, the presence of the shielded window always makes the overall consumption rise.

However, from the energy conservation point of view, a wavelength selective glass (Building B3) always proved to be more effective than the electrochromic device, regardless the climate and the installed lighting electric power.

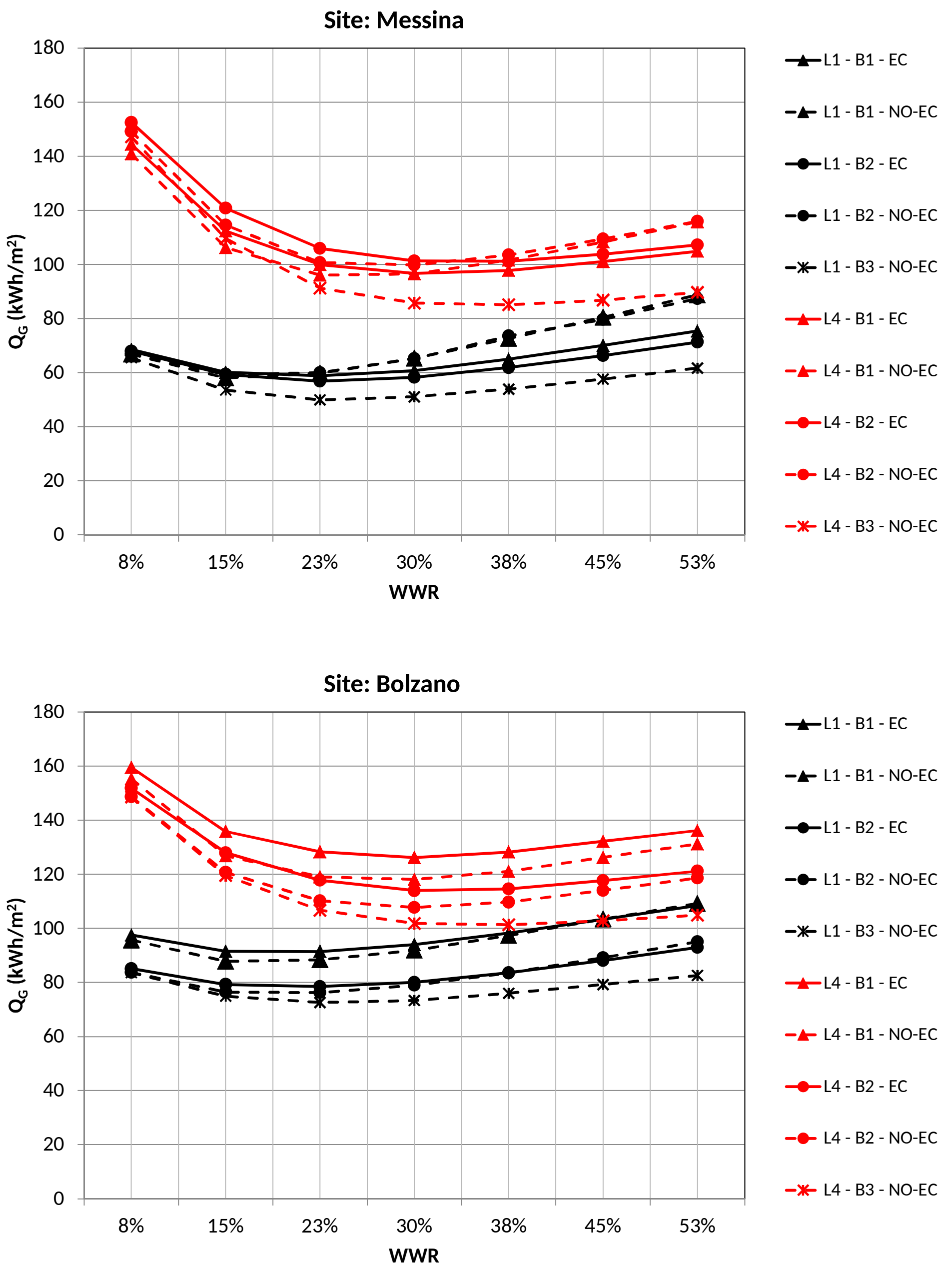
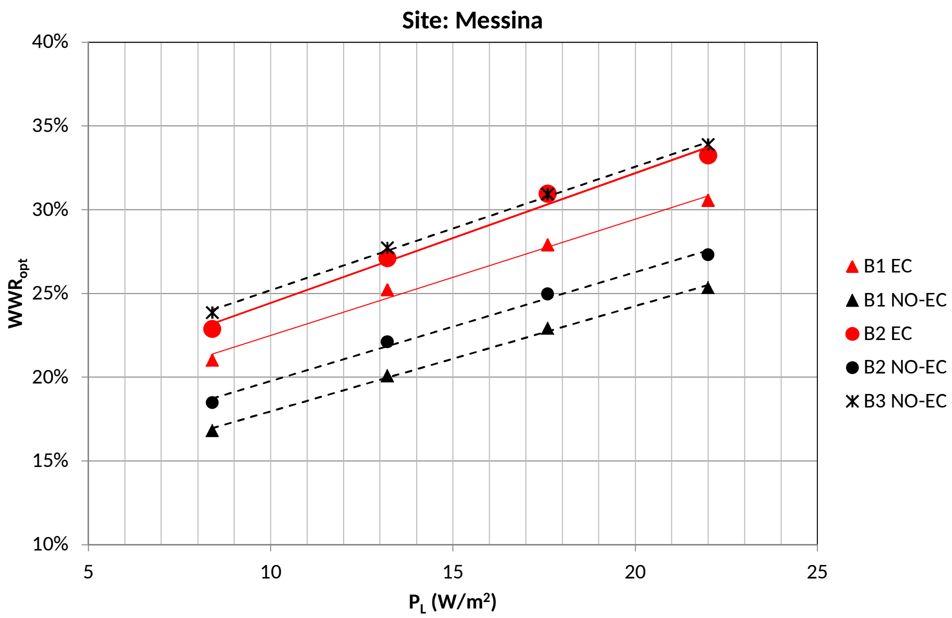



**Figure 24. Global Primary Energy Consumption versus WWR.**

As regards the optimal window surface, the presence of the shielded window always enhances the value $WWR_{opt}$ owing to the growth of the lighting consumption. This behavior is depicted in Figure 25, which reports the trend of $WWR_{opt}$ versus the installed lighting electric power $P_L$. The maximum variations were assessed for the warmer climate of Messina, where, for building B2, $WWR_{opt}$ rose of about 5% on average because of the electrochromic glass.



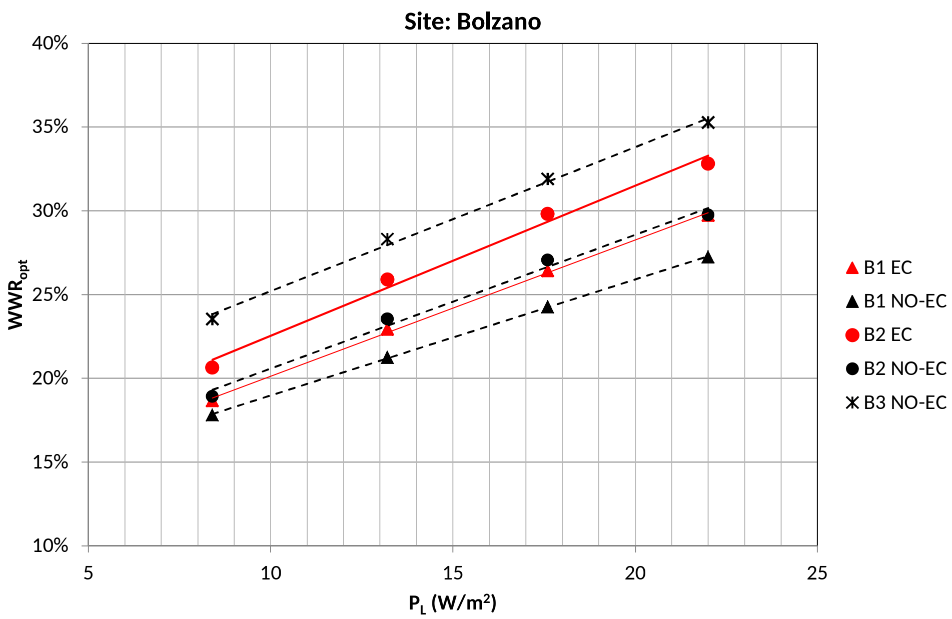




**Figure 25. Influence of installed lighting electric power $P_L$ on the optimum value of WWR in case of electrochromic windows.**

# 4 Conclusions

Conventional wisdom is that the proper design of the building envelope, which should appropriately consider the climate condition of the location site, is a crucial phase of the construction process on the grounds that optimal levels of energy efficiency have to be reached in order to comply with environmental law requirements and contribute to climate change containment.

In this context, the proposed study outlines the structure and the correspondent results of an analysis which might be exploited by designers, construction industry, construction insiders and researchers with a view to optimizing the façade configuration of buildings by varying the sizes of crucial components such as window systems.

The purpose of the analysis was to verify the existence of an optimal size of the window surface, which is the size allowing minimum overall energy consumption, and the variations that this optimum might undergo whether climate conditions, insulation features of the façade or luminaries input power change. In addition, the effect of a smart switchable shading device was also examined.

The analyses were performed using Energy Plus simulation code and an office building, whose structure and configuration represent a typical reference case for the Italian building stock, was modelled. The window dimensions were evaluated in terms of the ratio between the glazed surface and the gross façade area, which is referred to as window to wall ratio (WWR).

The results show that, notwithstanding the obvious variations of the overall energy consumption, the optimum value of WWR ($WWR_{opt}$) is slightly influenced by climate conditions and the insulation features of the envelope also seem to have a poor effect on this parameter as well.

As a matter of fact, the standard deviation of the $WWR_{opt}$ values assessed for the 12 considered climate conditions is equal to 1.1 % , for the least insulated building (B1), to 1.3% for the most insulated building (B2). The average values are of 23.5% for the least insulated building (B1), of 25.9%% for the most insulated building (B2).

On the contrary, larger window surfaces are allowed if spectral selective glazing is installed (building B3). In this case, the results inferred for all the considered climates, yield an average $WWR_{opt}$ of about 32% with a standard deviation of 1.2%.

As far as the luminaries features are concerned, a variation of about -14 $W/m^2$ (separating the two extreme configurations L4 and L1) of the installed lighting electric power, $P_L$, strongly affects the energy consumption in both cold and warms climates, and $WWR_{opt}$ undergoes a reduction ranging between -0.09 and -0.12 for all the examined building configurations.

The smart switchable shading devices, which might be needed for comfort requirements, cause a rise of the lighting consumption and a reduction of the cooling one which, in warmer climates, is a crucial issue for energy conservation purposes. According to this statement, the shaded windows allowed a remarkable reduction of energy consumption at Messina site when WWR exceeded a crucial value which essentially demonstrated to be dependent on the installed lighting electric power, $P_L$.

In colder climates the presence of the shield always seems to increase the overall energy consumption.

Furthermore, from an energy efficiency perspective, the spectrally selective glazing structure (building B3) demonstrated to be more effective than the switchable window pane, in all the studied climates.

As regards the influence of solar screens on $WWR_{opt}$, the presence of the shielded windows do not seem able to alter the value of this parameter remarkably; it rises for the effect of the shield, but the average observed increase was +0.05 in Messina, +0.03 in Bolzano.

In conclusion, albeit energy consumption demonstrated to be strongly influenced by climate conditions, insulation features of the structures, façade configurations, presence of shading devices, the optimal $WWR_{opt}$ does not seem to vary remarkably if the effect of each factor is assessed individually. Remarkable variations were conversely observed when the combined influence of different issues was taken into account: regardless the climate conditions, $WWR_{opt}$ may be doubled for the simultaneous effect of an improvement of the envelope features and of an enhancement of the installed lighting electric power.

However, the major influence seems to be exerted by the input electric power of the luminaries which, therefore, should be carefully considered during the building design phase which in turn is to be planned as an integrated process regarding envelope structures and systems at the same time.

Nevertheless, it is worth highlighting that there are more design factors calling for further investigation in the future research, such as, for example, the influence of the position and shape of the window. In this direction future analysis is to be planned.

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