Assessing the lighting systems flexibility for reducing and managing the power peaks in smart grids

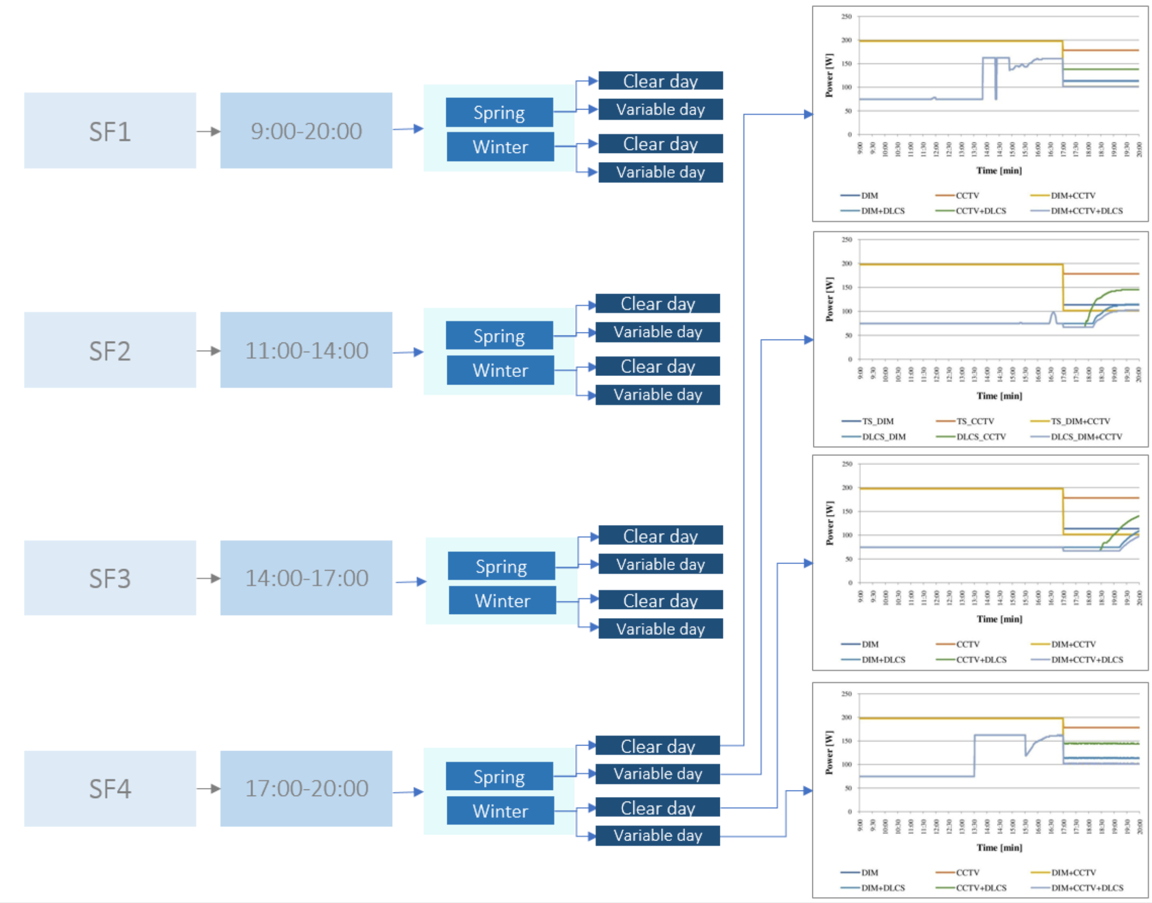
Marco Beccali[1], Laura Bellia[2], Francesca Fragliasso[2], Marina Bonomolo[1], Gaetano Zizzo[1,] Gennaro Spada[2]

[1] Università degli Studi di Palermo

[2] Università di Napoli Federico II

Abstract: The application of “shiftable” or “modulable” load (i.e. washing machine, dishwasher, etc.) in a Smart Grid, can provide energy saving or modify the power flows in the grid, allowing a reduction of the electrical power peak. This paper explores the possibility to modulate the indoor artificial lighting to support this reduction. The study examines the impact of two different measures of power shaving. On the one hand, the change of Correlated Colour Temperature of the light source, and, on the other hand, the dimming of its luminous flux. The possibility to merge the above-mentioned technical solutions is also analyzed. Based on these strategies, several daily schedules of lighting management are defined, and the corresponding energy saving during some critical time slots are assessed. Results show that in all cases, it is possible to achieve a significant reduction of the absorbed power and a consequent increment of energy savings (up to 59%) also in specific time ranges. Furthermore, considering the application of a Daylight-linked control system, it was observed that power regulation associated with the exploitation of the daylight represents itself a way to dynamically reduce the electric loads on the grid.

Graphical Abstract



Keywords: lighting; BAC; energy efficiency; modulable loads.

1. Introduction

The use, increasingly common, of smart and controllable appliances, is making the electric grid more and more flexible [1]. Indeed, electric loads' shifting and modulation provide an innovative solution to the problem of the electric power grid management [2].

Moreover, load shifting has a significant potential to save energy and, consequently, it can help in lowering the electricity bills of the consumers while reducing the electric power peak [3].

Many research studies focused on the possibility of controlling various devices and appliances [4], such as DHW production systems, ventilation and air-conditioning systems and heating [5], etc.. DR can be a significant solution to promote renewable energy consumption and improve energy efficiency in integrated energy systems [6]. As an example, in [7] the authors propose a method for estimating the Demand Response

(DR) potential of heat pumps based on measurement data while in [8] heat pumps modulation by heuristic control strategies is proposed. In [9], smart electric vehicles' batteries are managed for providing DR services. In [10] the authors propose and validate a dynamic model of a Water Booster Pressure Systems for flexibility provision, while the study in [11] shows how water distribution systems can profitably be used for DR.

In [12], the authors assessed the impact of demand response actions in service and residential sectors using internal balancing tools which are able to mitigate the imbalances of an aggregator, caused by uncertain solar generation. Ihsan, Jeppesen and Brear [13] developed a model, applied in an educational case study in Victoria, useful to optimize a hybrid power plant connected to a grid including the use of DR, historical local solar irradiance and demand traces. Afzalan and Jazizadeh [14] focused their attention on the issue that DR schemes are not able to distinguish the ranging potential of user actions due to the highly-varied usage behaviours. Authors presented a data-driven approach useful to quantify the potential of individual flexible load users.

In [15], the authors proposed a solution for demand-side management involving and agent-based architectures that were deployed in a small office, taking into account as well as the lighting load.

As seen, the literature on DR is short of studies that considered lighting as modulable load. Most of the studies mentioned above included other devices in their analysis as well because the "flexibility" consists in the possibility to shift the loads. Instead, the other studies did not include lighting as a flexible resource, since it is necessary to switch on the lamps when the light is needed and, independently of the time of day, it is not possible to shift the related electric load. Nevertheless, lighting has a high relative share of power consumption in offices. As an example, a study conducted by EURAC [16] shows that in EU-27 office buildings the annual energy consumption for domestic hot water is 7 TWh/year with an average of 10 kWh/m^2 per year, for cooling is 18 TWh/year with an average of 22 kWh/m^2 per year and, finally, for lighting is 42 TWh/year with an average consumption of 39 kWh/m^2 per year. These data give a clear indication on the importance of trying to manage the electric load for lighting for DR purposes.

However, nowadays, thanks to the use of the available smart and dynamic lighting systems, it is possible to implement daily scheduling describing how luminaries' luminous flux emission changes in time, varying in terms both of intensity and of Correlated Colour Temperature (CCT) [17]. CCT is one of the most crucial lighting factors to influence subjective perceptions, but as well a strategy to save energy [18]. By using smart devices, the electric load for lighting can be modulated and not precisely "shifted" as for the other loads. Indeed, as explained above, it is not useful to shift in the time the lighting because users need lighting in a specific time. On the basis of the above considerations, in this study, the authors considered the "modulation" of the absorbed power. This means that the characteristics of the luminous flux emitted by light sources can be modified in order to reduce the related absorbed power in specific periods of the day. This goal can be achieved using different technical solutions. As an example, the old Italian Standard UNI10380 [19] established a range of useful illuminance values for every task and not a minimum value to be fulfilled. Therefore, according to the spirit of this standard, illuminance levels at the work-plane could be varied within this range during the operative hours and reduced when necessary for achieving a correspondent electric load reduction. Similarly, a variation of the power absorbed by the lighting system can be obtained by changing the CCT as well because of the spectral dependence of luminous efficiency of the sources. Moreover, as well-known, artificial lighting can be decreased according to the natural one availability.

It must be stressed that the modifications of the CCT and of the illuminance could have a positive impact both in terms of comfort conditions improvement (especially considering the so-called non-visual effects) and in terms of energy costs reduction. Indeed, lighting characteristics can widely influence the circadian rhythms [20], well-being and health, especially in the case of users affected by particular diseases [21]. Figueiro, Gonzales and Pedler [22], underlined that lighting designed with a focus on the circadian effects is different from traditional "architectural" lighting design. Generally, in the latter case, there is particular attention on comfort, visibility and, consequently, safety, reduction of the glare and the appearance of the space. It must be reminded that the new Energy Performance of Buildings Directive (EPBD) prescribes the exploitation of a European scheme for evaluation the *smartness* of the buildings: the "Smart Readiness Indicator" (SRI) [23]. It mainly depends on the presence of "smart ready services" in a building. These services can be referred to multiple domains and have an impact on several aspects (comfort, energy savings, flexibility towards the energy grid, etc.). The considered domains are lighting, cooling, dynamic building envelope, domestic hot water, heating, ventilation, on-site renewable energy generation, demand-side management, electric vehicle charging and monitoring and control. The calculation method has a multi-criteria approach, and it is based on a set of weights. Three key functionalities of smartness are considered in the described method, one of them is "the flexibility of a building's overall electricity demand, including its ability to enable participation in active and passive as well as implicit and explicit demand-response, in relation to the grid, for example through flexibility and load shifting capacities".

In view of this, the goal of this paper is to investigate and evaluate the possibility to reduce the power absorbed by lighting systems in specific periods of the day for providing flexibility to the grid. This is achieved by varying the illuminance at the work-plane within a well-specified range and the CCT of the lamps, while preserving the end-users' comfort. The study is done considering a typical office building application and evaluating, at the same time, the energy consumption reduction due to the use of daylight-linked control systems. To simulate the operation of such a system, data obtained by means of on-field daylight measurements are used and, according to the analysis of the results, the limits and the efficacy of feasible strategies of load-modulation are assessed.

From a technical point of view, this kind of operation in a smart grid framework is feasible thanks to the technical solutions for lighting and building automation present on the market. As an example, the Italian Technical Standard CEI 205-18 proposes some possible installation layouts for lighting control in buildings allowing a reduction of the energy consumption for lighting purposes [24]. Moreover, the management strategies proposed in this paper are in line with the more recent experiments on load aggregation in Italy promoted by the Deliberation ARERA 300/2017/R/eel. In the ongoing experimentation, prosumers are requested to reduce their demand with time step of 15 minutes, perfectly obtainable with the systems and management strategies that are presented in the rest of the paper. Finally, as it will be shown in the following, in some cases a reduction of about 50% of the total power consumption from lighting can be achieved. Such a reduction, in case of very large buildings, can lead to significant variations of the power demand of the building (in the order of tens of kWs), comparable to those derived from the management of other electric loads. Taking into account the data on energy consumption for lighting collected by EURAC [16], this reduction can have a very significant impact on DR in smart grids.

The rest of the paper is organized as it follows. Section 2 presents the proposed methodology, the case studies and the scenarios analysed in the paper; section 3 reports and discusses the results of the study and, finally, section 4 contains the conclusion of the work.

2. Methodology, case study and scenarios description

A simple office was used as a case study. Here, the lighting system operation was analysed in different operative conditions, in order to quantify the energy saving due to the application of each selected management strategies. In particular, two lighting system base cases were considered. The former was a traditional system without Daylight-linked Control Systems (DLCS) (indicated as TS from now on), the latter was a daylight-linked control system (indicated as DLCS from now on).

The following management strategies were applied to each base case:

- Reduction of the luminous flux, considering that the work-plane illuminance can be regulated from a minimum to a maximum value (DIM);
- Variation of CCT (CCTV);
- Combination of DIM and CCTV (DIM+CCTV).

It must be underlined that, in the case of the DLCS, actually, the luminous flux was continuously regulated between a minimum and a maximum level, in order to integrate daylight. So, the DIM strategy applied to the DLCS implied that the flux regulation was based on daylight availability as well. However, the system was calibrated such that the maximum light output was lower than when the DIM strategy was not considered.

The strategies were applied in specific daily time ranges shown in Figure 1. The time range F1, between 09:00 and 20:00, F2, between 11:00 and 14:00, F3 between 14:00 and 17:00 and, finally, F4 between 17:00 and 20:00.

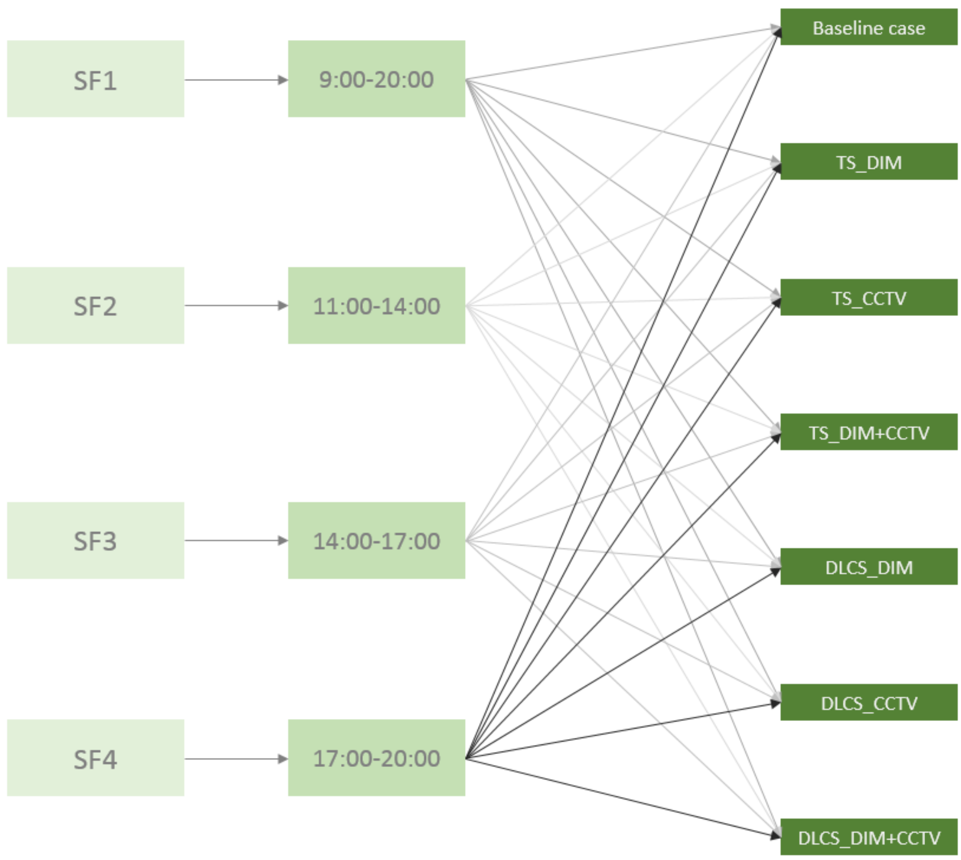


Fig. 1. Flux diagram of the tested scenarios.

These ranges are the ones often adopted in time-related tariff schemes by electricity providers. Four corresponding daily schedules were defined for these time ranges: SF1, SF2, SF3, SF4.

For example, when the DIM is applied to the TS (TS_DIM) according to the SF1 schedule, luminaires flux is set low during F1 (i.e. during the entire working day, from 9:00 to 20:00). Adopting the schedule SF2, the luminous flux is set high for the entire day, except than in the F2 (11:00-14:00), when it is automatically reduced. The same happens for the DLCS base case and for the other strategies and time ranges. For example, if the CCTV is applied to the DLCS (DLCS_CCTV) according to the schedule SF3, the CCT is set to a low value during the entire day and to a higher level during the period F3 (between 14:00 and 17:00).

The time range F1 was considered in order to verify how the variations of the CCT and the task illuminance affect daily energy consumption. F2, F3 and F4 were chosen in order to quantify the lighting energy reduction in specific moments of the day and consequently check the feasibility of such strategies in reducing the power peak. Exactly, F2 represents a time range characterized by high electricity price (peak pricing). F3 and F4 are two different three-hours periods between 14:00 and 20:00, during which a load aggregator can request an electric load reduction. For instance, this has been done for an experimental study on small prosumers aggregation in Italy [25, 26]. The energy consumption of the lighting system for all the time ranges was calculated in the two base cases (TS and DLCS) and then, considering all the control strategies listed above. Finally, the results for the base cases and in the presence of the management strategies were compared and analysed. In this regard, the study was organized in different steps. First of all, the characteristics of a chosen white-tuning LED source were tested in a laboratory, to quantify the absorbed power variations due to both CCT and luminous flux regulations. Moreover, daylight measurements were made in the office used as a case study in order to obtain data useful to simulate the DLCS in different daylight conditions. Then, a lighting system suitable for the office was designed using DIALux software, using the previously tested luminaires. Finally, through all the collected data, it was possible to simulate the functioning of the designed lighting system in the different operative conditions to calculate the energy saving.

2.1. Laboratory measurements

The chosen light source was a white tuning LED. According to the manufacturer’s technical sheet, it is characterized by the following features: luminous flux= 4280 lm, power= 51 W, Colour Rendering Index > 80, CCT variable in the range 3000 K - 6000 K. Figure 2 reports LED photometry and Figure 2 the spectral power distributions for the two CCT limit levels, measured by means of a CS 2000 Konica Minolta spectroradiometer [27, 28].

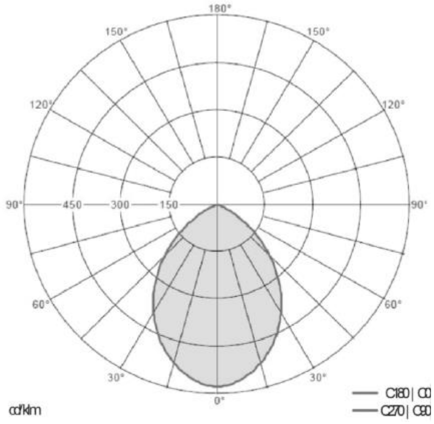


Fig. 2. Photometry of the luminaire used for the test in the laboratory.

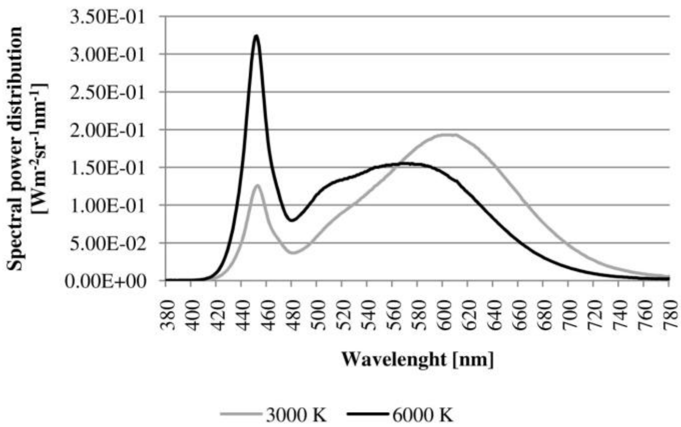


Fig. 3. Spectral power distribution of the light sources used for the test in the laboratory.

The LED lighting sources were installed in the Photometry and Lighting Laboratory of the Department of Industrial Engineering of the University of Naples Federico II (Italy). The laboratory dimensions are reported in Figure 4. The room is a neutral environment. The four perimeter walls are covered by white curtains characterized by an 83.45% reflectance factor (reflectance factors are referred to the D65 illuminant). In contrast, the ceiling and the floor are characterized by 82.32% and 58.61% reflectance factors respectively. Luminaires are connected to a DALI control unit (a touch panel), allowing not only the CCT to be varied but also the luminous flux to be regulated from a maximum value (indicated by the touch panel as 100%) to a minimum one (indicated by the touch panel as 1%).

Five different luminous flux levels (LFLs) were chosen to perform measurements: 100%, 75%, 50%, 25% and 1%. For each level, the CCT was varied from 3000 K to 6000 K with 500 K steps. For each combination of LFL and CCT, the absorbed power was measured using an electronic power meter connected to the laboratory fuse-box. The illuminance at the work-plane was simultaneously monitored, using a Konica Minolta T10 illuminance meter [28]. It was installed on a horizontal plane, at a distance from the floor equal to 0.75 m and in correspondence of the luminaire's barycentre (P1 in Figure 4).

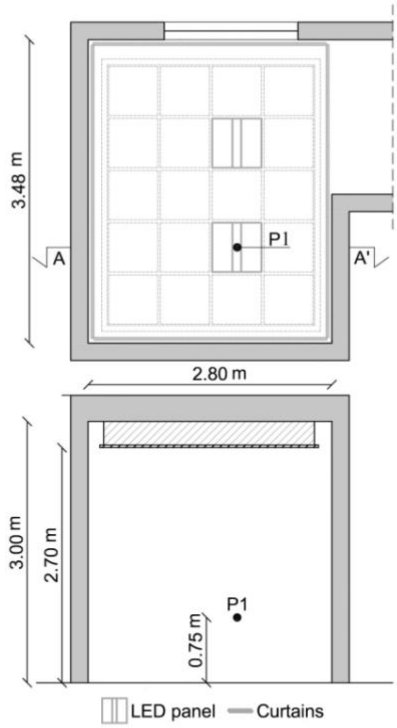


Fig. 4. Measured plan and section of the Photometry and Lighting Laboratory where luminaires have been tested in order to know the absorbed power ranges.

Figure 5 describes the variations of the absorbed power depending on CCT for the five chosen LFLs. The curves trends are decreasing and almost linear. Specifically, the absorbed power ranges:

- from 49.4 W to 44.1 W when LFL is 100%;
- from 42.2 W to 37.4 W when LFL is 75%;
- from 33.1 W to 29.7 W when LFL is 50%;
- from 25.4 W to 22.8 W when LFL is 25%;
- from 17.9 W to 16.0 W when LFL is 1%.

So, the reduction is always equal to 10-11%.

Moreover, it is interesting to notice that the relationship between the LFL and the absorbed power can be considered linear, but, when the LFL is equal to the minimum (i.e. 1%), the corresponding absorbed power is about 36% for the maximum one, for each considered CCT. For example, as it was previously reported, with a 3000 K CCT the power corresponding to the 100% LFL is 49.4 W, when luminaires are on at the minimum level, the power is 17.9 W (17.9/49.4= 0.36).

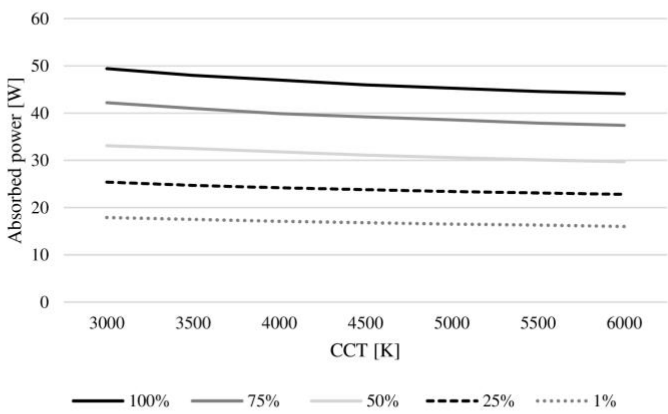


Fig. 5. Plotted measures of the absorbed power variations as a function of the CCT for the five LFLs.

Table 1 reports the average illuminances and the root-mean-square errors (RMSEs) obtained for each LFL changing the CCT.

Table 1. Average illuminances at the work-plane and root-mean-square errors.

LFL [%]	Average illuminance [lx]	RMSE [lx]
100	327	1.1
75	273	0.9
50	217	0.69
25	164	0.7
1	112	0.4

The RMSE values are all very low, demonstrating that the CCT variation determines illuminance oscillations at the work-plane completely negligible (1-2 lx). Table 1 clearly shows that the LFL indicated by the controller does not correspond to the actual percentage of the emitted luminous flux. Indeed, when the LFL is equal to 1%, the emitted flux is actually 34% of the total one (112 lx/327lx). From now on, the actual percentage of the emitted flux to the total one will be called light output and will be indicated with δ.

2.2. **Daylight irradiance and illuminance measurements**

Daylight irradiance and illuminance measurements were performed in the office used as case-study. The office is located in Naples (Latitude 40° 51' 22 N, Longitude 14° 14' 47 E) and its dimensions are reported in Figure 6.

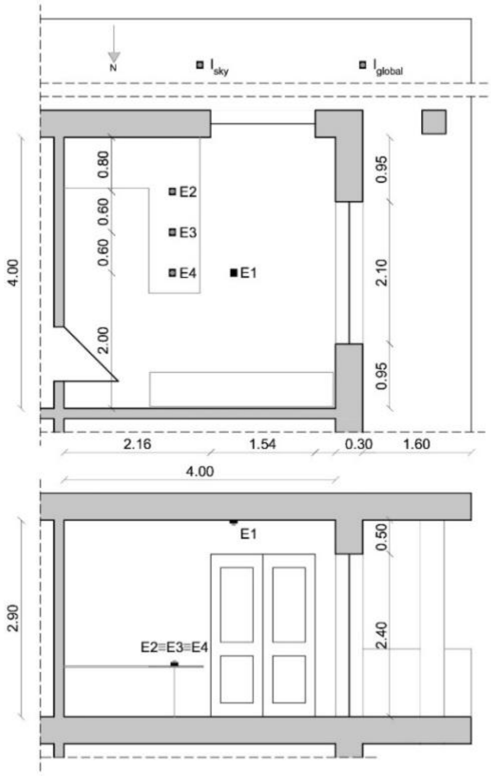


Fig. 6. Measured plan and section of room selected as case study.

Reflectance factors of architectural surfaces were the following: 84.61% for the ceiling, 76.37% for the walls, 53.36 % for the desk, 50.70% for the furniture. The room is equipped with two balcony windows: one facing West and the other facing South. In order to modify the window to wall ratio and evaluate different façade configurations, some cardboards, characterized by a finish similar to the room walls, were attached to the windows frame, to cover part of the glazed surface, according to different patterns.

Four cases study were so obtained as it is reported in Figure 7:

- south orientation with balcony window (A configuration);
- south orientation with simple window (B configuration);
- west orientation with balcony window (C configuration);
- west orientation with simple window (D configuration).

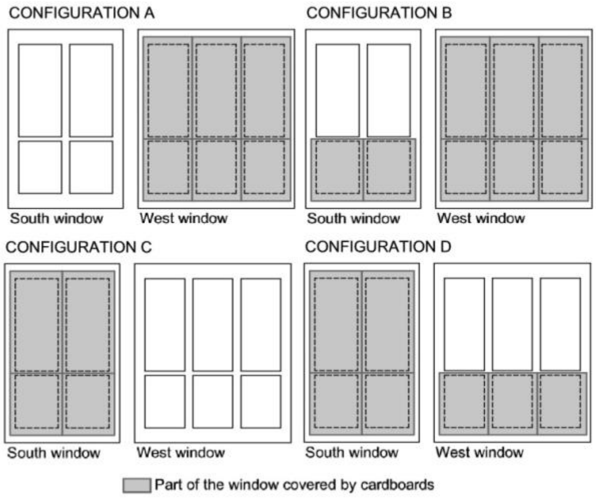


Fig. 7. The four different façade configurations chosen to simulate the scenarios with DLCS.

In order to simulate a DLCS, it is necessary to know the daylight levels both at the work-plane and at the photosensor managing the lighting system. For this reason, three NESA illuminance sensors [29] were positioned on the desk at a mutual distance equal to 0.60 m. Another sensor was ceiling mounted and looking downward. Daylight illuminances were monitored from 9:00 to 20:00 with a one-minute time step. Simultaneously, outdoor global irradiance was measured by means of a NESA RSG pyranometer [30]. Measurements were performed both during spring and during winter, one week for each façade configuration. Then, for each case study, two days were selected: the former predominantly characterized by a clear sky and the latter by variable weather conditions, as represented in Figures 9 and 10, where the irradiance trends related to the considered days are reported for both winter and spring. Analyzing several façade configurations and extremely different weather conditions allowed evaluating how energy saving due to DLCS use varies according to daylight availability.

2.3. Base cases lighting system description

A lighting system suitable for the office described in the previous section was expressly designed by using the Dialux software, considering the luminaire tested in the laboratory and described in Section A. The office was often used for architecture students tutoring. In such a case, the supposed visual task is *technical drawing*. For this activity, the European standard 12464-1 [31] appoints an average maintained illuminance equal to 750 lx and a uniformity value of 0.70. On the other hand, the requirements related to "Writing, typing, reading, data processing" are 500 lx and 0.6. Clearly, the system was designed considering the most urgent requirements. To meet them, four LED panels (arranged in two rows) were necessary. Such a system, considering a maintenance factor equal to 0.80, would provide at the desk an average illuminance equal to 778 lx with uniformity equal to 0.85. With this system configuration, it was assumed that in the TS case, luminaires CCT is equal to 3000 K. According to the laboratory measurements, the system total installed power is equal to 197.6 W (49.4 W per luminaire). As for the DLCS base case, LED CCT was equal to 3000 K as well, but luminaires instead of remaining switched on for the entire day were regulated to integrate daylight. In particular, it was assumed that the lighting system was managed by a closed-loop proportional dimming control system, the operation of which was simulated by using the previously measured daylight data. It was considered that the ceiling-mounted illuminance sensor was the photosensor detecting indoor light. Starting from the measured values, by applying the control algorithms represented in Figure 7 [32] and using the calibration parameters reported in Tables 3 and 4, the luminaires light output (δ) daily trends were calculated. Finally, starting from the obtained data, the related absorbed power trends were obtained.

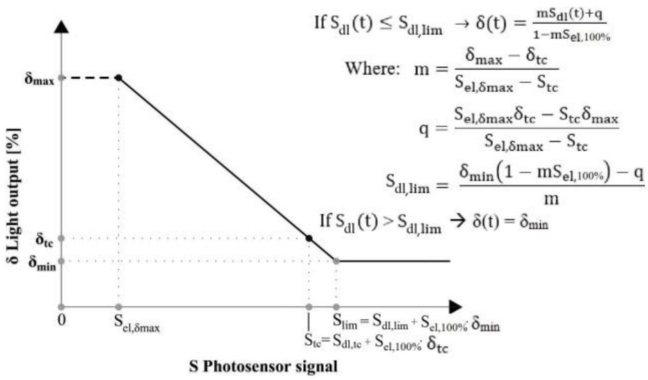


Fig. 8. DLCS control algorithm used to calculate the daily trends of the luminaires light output.

Table 2
Parameter and definition

$S_{dl}(t)$	Daylight photosensor signal as a function of the time	[lx]
$\delta(t)$	Luminaires light output as a function of the time	[%]
δ_{max}	Maximum luminaires light output	[%]
δ_{tc}	Luminaires light output at the calibration	[%]
δ_{min}	Minimum luminaires light output	[%]
$S_{el,100\%}$	Electric light photosensor signal when luminaires are on at 100%	[lx]
$S_{el,\delta max}$	Electric light photosensor signal when luminaires are on at δ_{max}	[lx]
$S_{dl,tc}$	Daylight photosensor signal at the calibration	[lx]
$E_{dl,tc}$	Work-plane daylight illuminance at the calibration	[lx]

Table 3
LCS control parameters for DLCS strategy.

Parameter	Definition	Value
δ_{max}	Maximum light output	80%
$S_{el,100\%}$	Electric light photosensor signal when luminaires are on at 100%	355 lx
$S_{el,\delta max}$	Electric light photosensor signal when luminaires are on at δ_{max}	284 lx
δ_{min}	Minimum light output	34%

Table 4
DLCS calibration parameters for DLCS strategy

Façade conf.	**Season**	**Daylight photosensor signal at the calibration $S_{dl,tc}$ [lx]**	**Work-plane daylight illuminance at the calibration $E_{dl,tc}$ [lx]**	**Light output at the calibration δ_{tc} [%]**
A	Winter	390	420	36
	Spring	300	325	46
B	Winter	297	335	45
	Spring	409	367	41
C	Winter	505	359	42
	Spring	366	365	42
D	Winter	406	351	43
	Spring	453	351	43

It must be underlined that δ_max was assumed to be equal to 80%, since, due to the maintenance factor use, in the first phase of the system operative life, to obtain 750 lx at the work-plane, the luminous flux can be reduced. The electric light signals were calculated in Dialux [33], whereas the daylight conditions at the calibration were obtained by selecting proper values from the measured data archive.

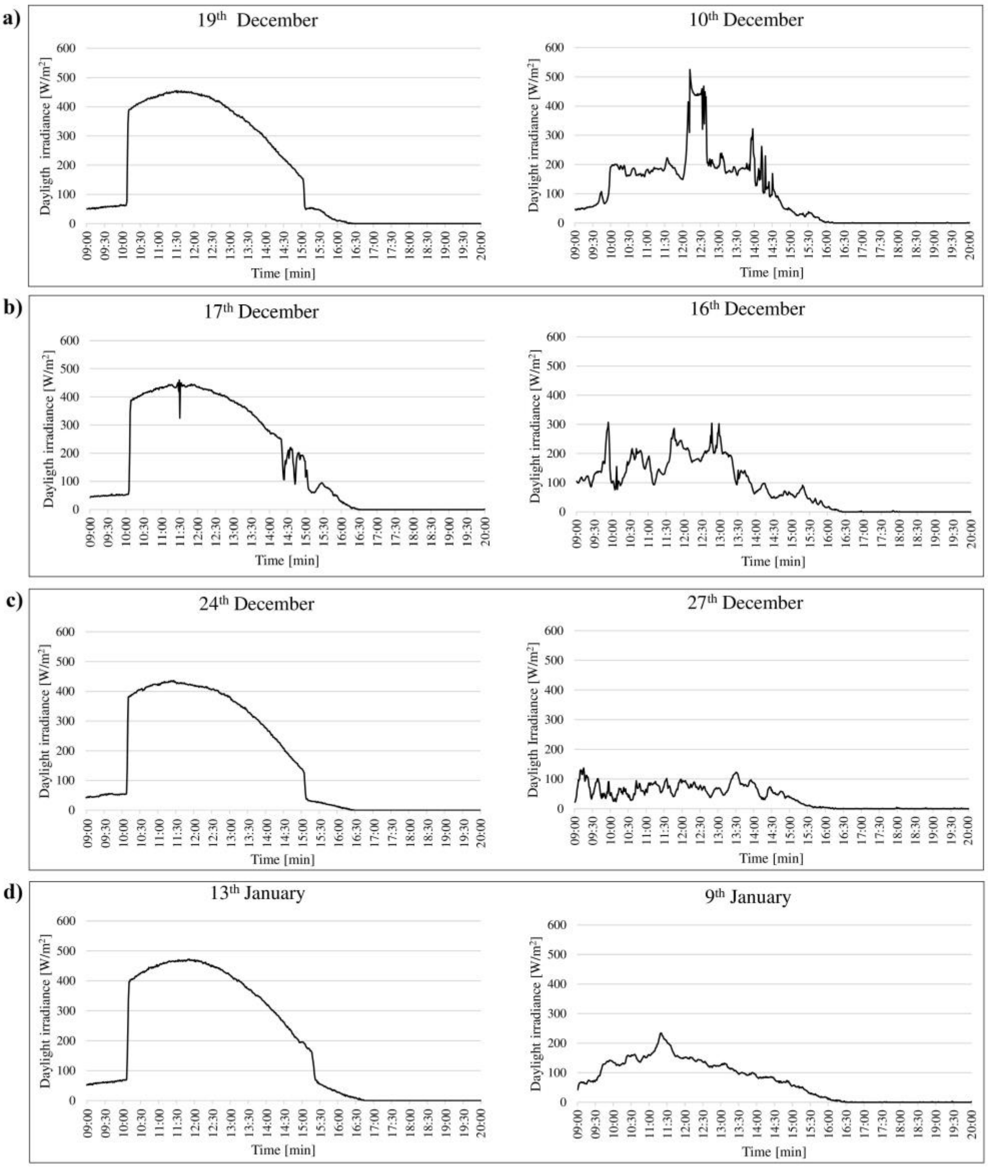


Fig. 9. Plotted data of the daylight irradiance trends measured during winter for the four different facade configurations.

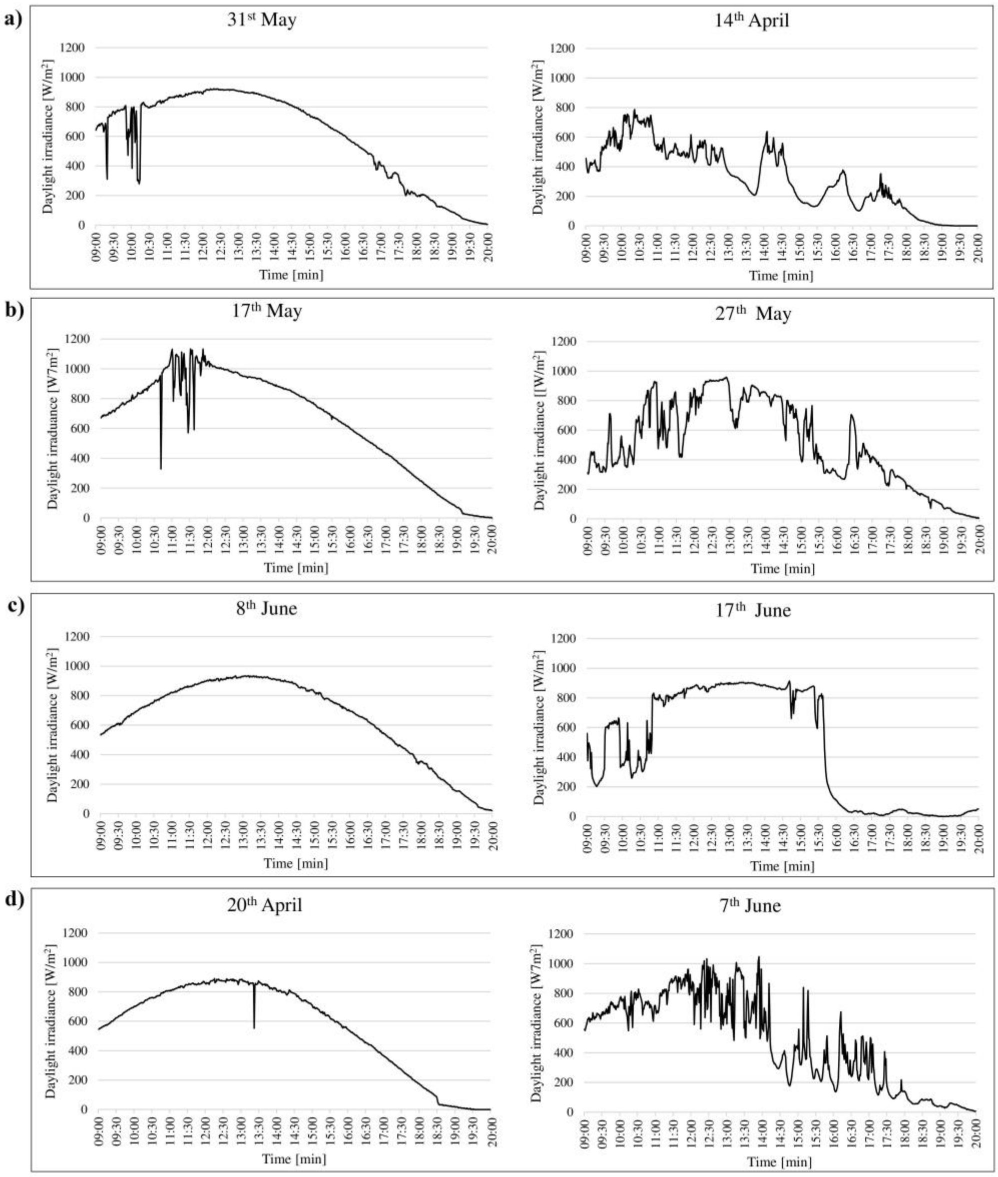


Fig. 10. Plotted data of the daylight irradiance trends measured during spring for the four different facade configurations.

2.4. Management strategies description

The DIM strategy implies that the illuminance at the work-plane can be reduced from 750 lx to 500 lx (corresponding to the different visual task performed in the office). In this case, the CCT is constant and equal to 3000 K. To obtain 500 lx at the work-plane, luminaires light output must be equal to 55% of the maximum. According to the linear relationship between light output and absorbed power observed in the laboratory, 111.69 W correspond to this light output. As for CCTV, it was considered that CCT could be increased from 3000 K to 6000 K, with a consequent luminaire power decrease from 49.4 W to 44.1 W (total power equal to 176.4). Finally, when DIM+CCTV was applied, being the light output equal to 55% and the CCT equal to 6000 K, according to measurements, the corresponding power absorbed is equal to total power 99.76 W. For both DIM and CCTV it was considered that a controller consuming 2W was necessary. Moreover, in the case of DLCS, besides the controller, it was assumed that the required photosensor has a power consumption of 1 W.

It must be underlined that, when the DIM strategy is applied to the DLCS case, the control parameters must be different. They are reported in Tables 5 and 6.

Table 5
DLCS control parameters for DLCS _dim strategy.

Parameter	**Definition**	**Value**
δ_{max}	Maximum light output	55%
$S_{el,100\%}$	Electric light photosensor signal when luminaires are on at 100%	355 lx
$S_{el,\delta max}$	Electric light photosensor signal when luminaires are on at δ_{max}	194 lx
δ_{min}	Minimum light output	34%

Table 6
DLCS calibration parameters for DLCS_DIM strategy

Façade conf.	**Season**	**Daylight photosensor signal at the calibration $S_{dl,tc}$ [lx]**	**Work-plane daylight illuminance at the calibration $E_{dl,tc}$ [lx]**	**Light output at the calibration δ_{tc} [%]**
A	Winter	113	100	42
	Spring	80	100	45
B	Winter	74	100	46
	Spring	87	100	44
C	Winter	62	100	47
	Spring	99	100	43
D	Winter	87	100	44
	Spring	92	100	44

3. Results and discussion

3.1. Comparison between the two base cases

Considering that the office is occupied from 9:00 to 20:00, the daily energy consumption of the TS is equal to 2173.60 Wh.

As for the DLCS, its daily power trends are reported in Figure 11, referring to each facade configuration and day. It worth noting that, for the two South configurations, in winter, during the period ranging from 13:30 to 15:30, the system is often turned on at its maximum light output. The same happens for the two West configurations in spring from 17:00 on. The reason is that simulations were performed considering that, when daylight illuminance at the work-plane was too high, and it was likely to determine discomfort (i.e. it is higher than 3000 lx [34]), an ideal shading device was activated, preventing direct daylight entrance. Consequently, electric light was turned on at its maximum level. Moreover, it is interesting to notice that for South configurations, both with variable and clear sky, the system works at its minimum capacity for about half of the day.

The DLCS daily consumption values are reported in Figure 12. As it was easy to expect, the winter consumptions are higher than the spring ones. Moreover, in winter, the differences between clear and variable days can be remarkable, as it can be observed for C and D configurations. This is due to the fact that, as Figures 9.c and 9.d show, in these two cases the daylight availability during the variable days is scarce and irradiance values are shallow if compared with those measured during the clear days. On the contrary, in spring, these differences are not so stressed. This is due to the fact that, even when the sky is variable, daylight availability is so high that for most of the day, the system can work at its minimum capacity.

The daily energy saving achievable by using the DLCS with respect to the TS are reported in Table 7 for each considered day. They range from a minimum value of 23%, observed for C Winter variable, to a maximum one equal to 59%, observed for A Spring clear.

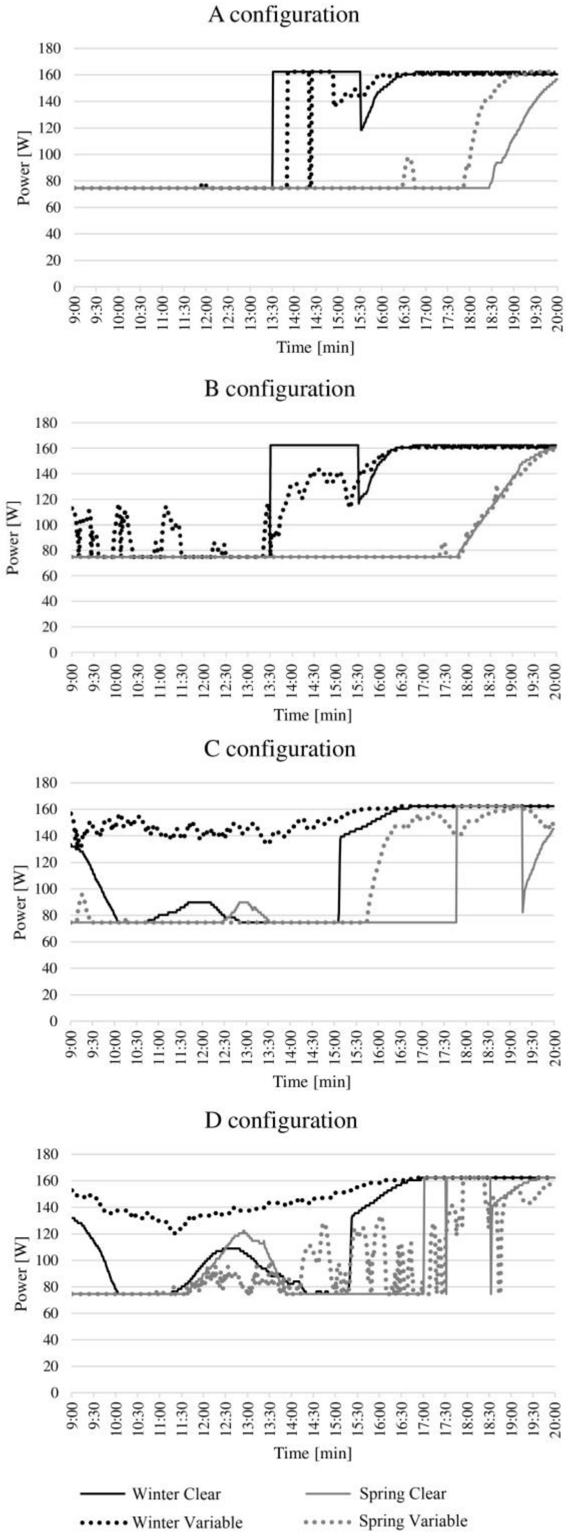


Fig. 11. Plotted data of the absorbed power trends measured for the four facade configurations.

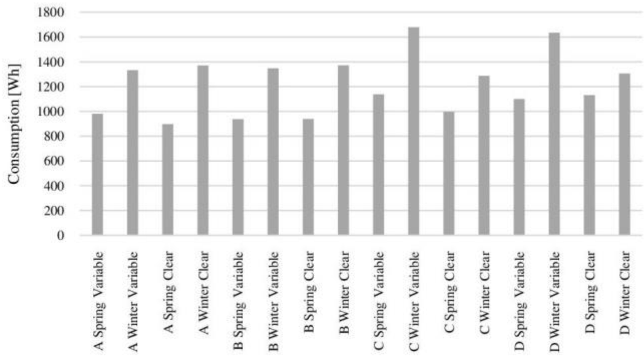


Fig. 12. Plotted data of the energy consumption calculated by considering the application of a DLCS in the base case for the four facade configurations.

Table 7
Saving achieved by means of the DLCS compared to the TS

Façade configuration	**Daily saving compared to TS [%]**
A Spring Variable	55
A Winter Variable	39
A Spring Clear	59
A Winter Clear	37
B Spring Variable	57
B Winter Variable	38
B Spring Clear	57
B Winter Clear	37
C Spring Variable	48
C Winter Variable	23
C Spring Clear	54
C Winter Clear	41
D Spring Variable	49
D Winter Variable	25
D Spring Clear	48
D Winter Clear	40

3.2. Application of the management strategies to the TS

Table 8 reports the daily consumptions obtained by applying the management strategies to the TS, both considering the SF1 and the SF2, SF3 and SF4. Moreover, the saving compared to the TS are indicated in the third and in the fifth column.

Table 8
Saving achieving applying the management strategies to the TS

Strategy	S_{F1}daily consumption [Wh]	S_{F1} daily saving compared to TS [%]	S_{F2}, S_{F3} and S_{F4} daily consumption [Wh]	S_{F2}, S_{F3} and S_{F4} daily saving compared to TS [%]
TS_DIM	1251	42	1922	12
TS_CCTV	1962	10	2116	3
TS_DIM+CCTV	1119	49	1886	13

Considering a task illuminance of 500 lx instead of 750 lx allows obtaining a 42% saving, whereas the variation of CCT determines a 10% saving. Combining the two strategies, the saving increases to 49%. Applying the strategy exclusively in one of the three-time ranges F2, F3 or F4, consumptions increases and the maximum achievable saving is equal to 13% due to the combination of the two strategies.

3.3. Application of the management strategies to the DLCS

Figure 12 reports daily consumption values obtained by applying the management strategies to the DLCS during the entire day (SF1). It can be observed that, as it was easy to expect, the highest consumptions were obtained for the DLCS_CCTV strategy and the differences between DLCS_DIM and DLCS_DIM+CCTV are always proportional. Sometimes the consumption differences referred to DLCS_DIM and DLCS_CCTV are not really significant (see for example A Spring Variable or A spring Clear). This happens when the DLCS works at the minimum of its capacity for most of the day (see Figure 10). In this case, the reduction of the task illuminance does not affect the consumption, since daylight availability is really high and electric lights are dimmed at the minimum light output, whatever the required illuminance is.

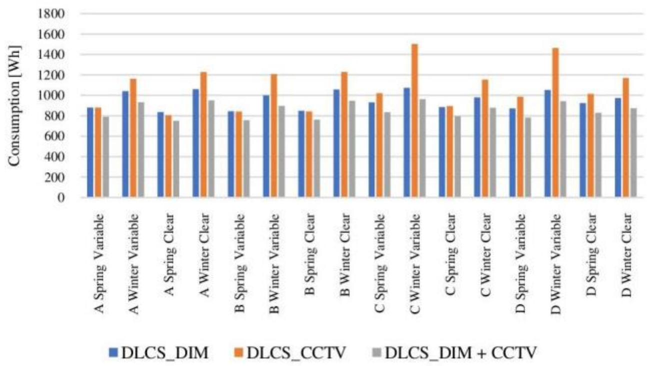


Fig. 13. Plotted data of the measured energy consumption referred to SF1 schedule for each control strategy and the four facade configurations.

By observing these consumption figures, the savings referred to the TS and the DLCS were obtained as well. Results are summarized in Tables 9 and 10. As it can be assumed comparing Table 9 to Table 8, the application of the strategies significantly increases the saving achievable by merely using the DLCS. In particular, as reported in Table 10, this additional saving can reach the 43% considering DLCS_DIM+CCTV.

Table 9
Minimum and maximum values of saving (compared to the TS) achieved by applying the management strategies to the DLCS and calculated according to the SF1

Strategy	Minimum saving compared to TS [%]	Maximum saving compared to TS [%]
DLCS_DIM	51	62
	Observed for C Winter variable	Observed for A Spring clear
DLCS_CCTV	31	63
	Observed for C Winter variable	Observed for B Winter variable
DLCS_DIM + CCTV	56	65
	Observed for C Winter variable	Observed for A Spring clear

Table 10
Minimum and maximum values of saving (compared to the DLCS) achieved by applying the management strategies to the DLCS and calculated according to the SF1

Strategy	Minimum saving compared to DLCS [%]	Maximum saving compared to DLCS [%]
DLCS_DIM	7	36
	Observed for A Spring clear	Observed for C Winter variable
DLCS_CCTV	10	13
	Observed for A Spring clear	Observed for A Winter variable
DLCS_DIM + CCTV	16	43
	Observed for A Spring clear	Observed for C Winter variable

Finally, the functioning of the DLCS_DIM, DLCS_CCTV and DLCS_DIM+CCTV were simulated according to the SF2, SF3 and SF4. In Figures 13-16, the power trends obtained by applying these strategies in

F4 are reported as an example. In the graphs, the trends of the same strategies applied to the TS are reported as well.

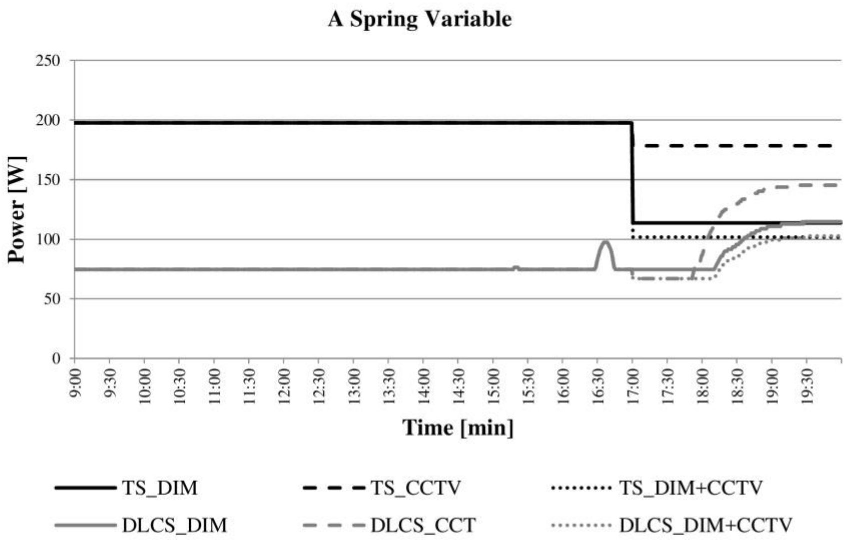


Fig. 14. Results of the calculation of the power trends referred to A facade configuration for the SF4 scenario (Spring-Variable day).

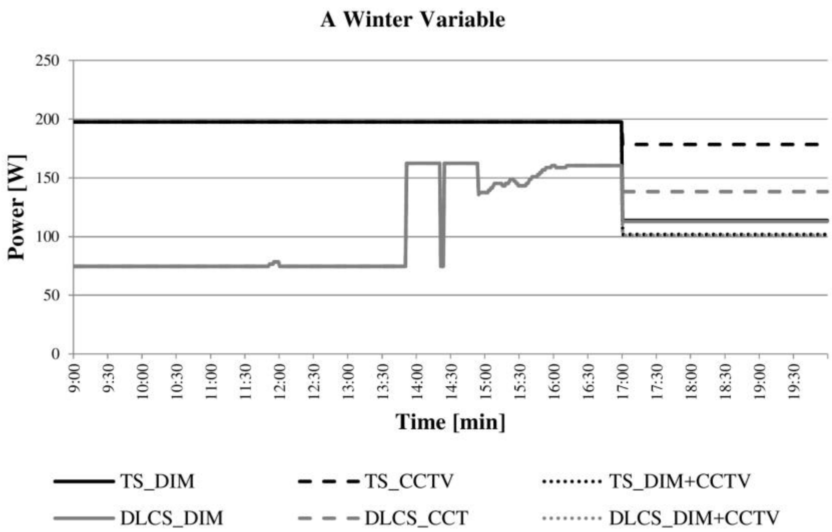


Fig. 15. Results of the calculation of the power trends referred to A facade configuration for the SF4 scenario (Winter-Variable day).

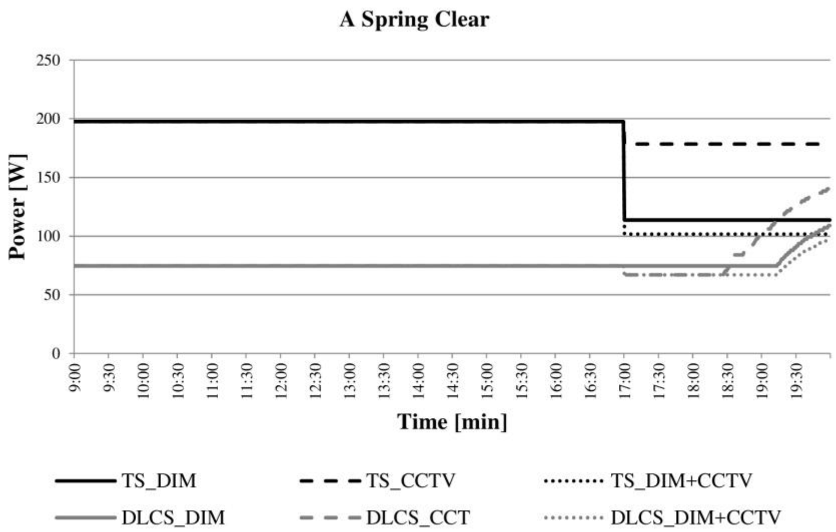


Fig. 16. Results of the calculation of the power trends referred to A facade configuration for the SF4 scenario (Spring-Clear day).

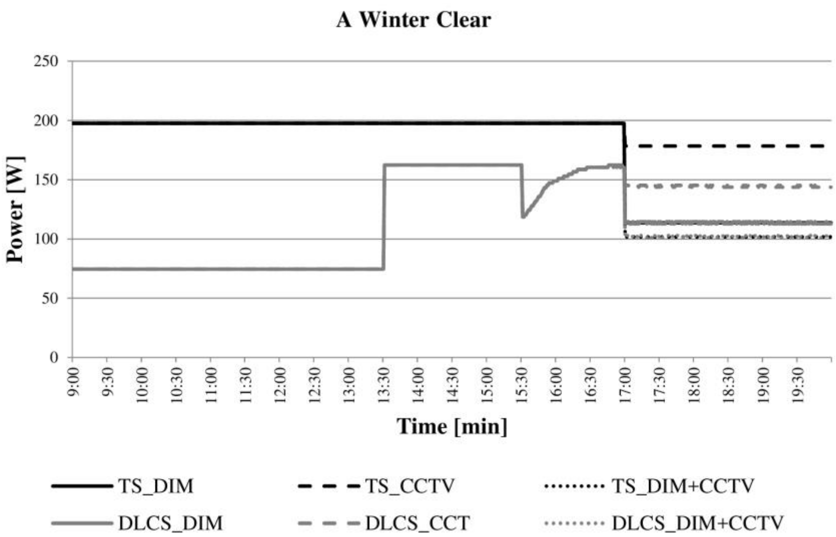


Fig. 17. Results of the calculation of the power trends referred to A facade configuration for the SF4 scenario (Winter-Clear day).

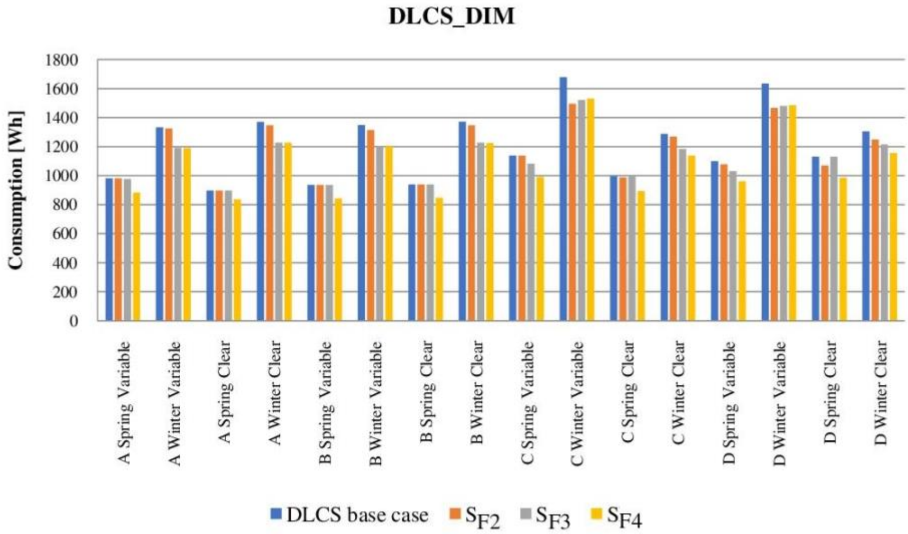


Fig. 18. Results of the daily energy consumption calculation referred to DLCS_DIM for each facade configuration for the scenarios SF2, SF3 and SF4.

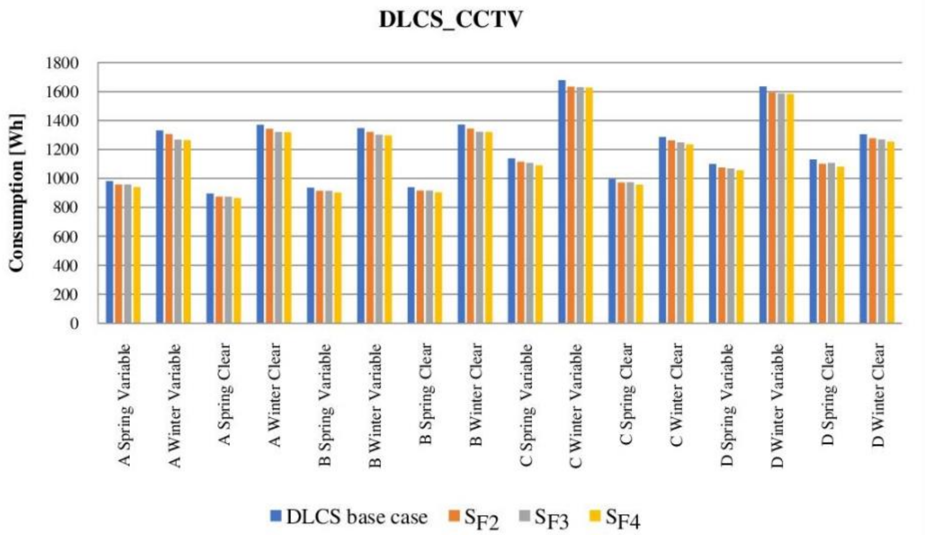


Fig. 19. Results of the daily energy consumption calculation referred to DLCS_CCTV for each facade configuration for the scenarios SF2, SF3 and SF4.

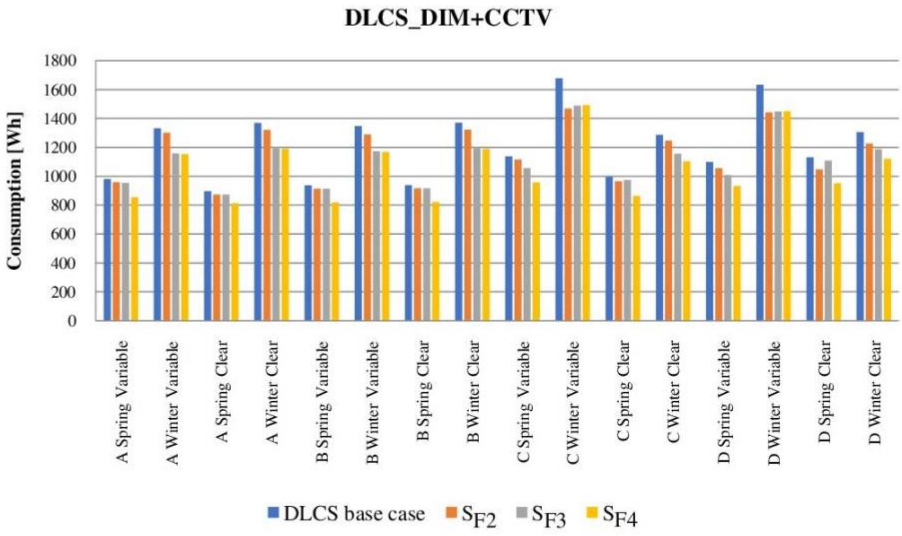


Fig. 20. Results of the daily energy consumption calculation referred to DLCS_DIM+CCTV for each facade configuration

Figures from 18 to 20 report daily energy consumptions referred to the three schedules S_{F2}, S_{F3} and S_{F4} for DLCS_DIM, DLCS_CCTV and DLCS_DIM+CCTV. In the diagrams, the consumptions related to the DLCS base case are also reported as a mean of comparison to make more accessible the comprehension of the data. For example considering the configuration A Spring Variable in Figure 18, comparing data of S_{F2}, S_{F3} and S_{F4} to the DLCS base case, it is clear that, when using the DLCS, the application of the DIM strategy in the two time ranges F2 and F3 is not effective, since the daily consumptions remain equal to the base case. On the contrary, the application of the same strategy in the F4 range is useful. In fact, it generates a reduction of the consumptions.

Considering the DLCS_CCTV (see Figure 19) for all the three schedules, a slight reduction of the energy consumptions can be observed compared to the base case. However, the consumptions for S_{F2}, S_{F3} and S_{F4} are really similar among them for all the observed configurations. This is due to the fact that, whatever the emitted luminous flux is, the increment of the CCT determines an always equal percentage reduction of the absorbed power. However, considering that due to the use of the DLCS the luminaires light output time series is not constant, the amount of saved energy expressed in Wh due to the CCTV strategy can be higher or lower depending on the functioning of the DLCS. When the system works at full capacity, the quantity of saved energy is higher, while, when the system works at minimum capacity, it is lower. For this reason, as it can be observed in Figure 19, the reduction of consumption is slightly higher for the S_{F4}. Indeed, for this schedule, the CCTV strategy is applied in the F4 time range (from 17:00 to 20:00) when the daylight availability is scarce and, consequently, the power absorbed by the electric light is high. In this condition, the percentage reduction of the absorbed power due to the CCT variation determines a higher reduction of the consumptions compared to the other schedules.

DLCS+DIM and DLCS+DIM+CCTV trends are very similar (Figures 18 and 20) because the CCT strategy effect is almost equal for each configuration. So, the results are comparable for the two strategies. First of all, it must be underlined that the reduction of the consumptions compared to the DLCS base-case assumes the maximum value in C Winter Variable and D Winter Variable when the daylight availability is scarce (see Figure 9). In spring consumptions for S_{F2} and S_{F3} are very similar to those of the base case, whereas they are lower for the S_{F4}, meaning that the application of the DIM strategy is less efficient in the F2 and F3 time ranges. This can be explained considering that the luminaires can be dimmed down until a minimum level. So, if the system works at full capacity (as during F4 when the daylight availability is low), the reduction of the light output due to the DIM strategy is effective. On the contrary, when daylight availability is high and light output low and close to the minimum level due to the use of DLCS (as in F2 and F3), the further applications of the DIM strategy is not so useful, and the daily consumptions remain similar to those of the base case. The only exceptions to this general spring trend are represented by the C Spring Variable and D Spring Variable (for which SF3 consumptions are intermediate between those related to SF2 and SF4) and D Spring Clear (for which SF3 consumptions are the highest ones). These differences are due to daylight availability as well. Also for winter, the lowest consumptions are observed for the S_{F4}, but for A and B configurations the values are low in S_{F3} as well, since the number of dark hours during winter is higher than in spring. Only in C Winter Variable and in D Winter Variable the consumptions are similar for all the three schedules because in these two cases daylight availability is low during the entire day.

Table 11
Minimum and maximum values of saving (compared to the TS) achieved by applying the management strategies to the DLCS and calculated referred to the specific time ranges

Strategy	Time range	Minimum saving compared to TS [%]	Maximum saving compared to TS [%]
DLCS_DIM	F2	35	66
	F3	29	66
	F4	26	55
DLCS_CCTV	F2	59	62
	F3	45	62
	F4	42	60
DLCS_DIM + CCTV	F2	63	66
	F3	51	66

	F4	48	64

Table 12
Minimum and maximum values of saving (compared to the DLCS) achieved by applying the management strategies to the DLCS and calculated referred to the specific time ranges

Strategy	**Time range**	**Minimum saving compared to DLCS [%]**	**Maximum saving compared to DLCS [%]**
DLCS_DIM	F2	0	43
	F3	0	33
	F4	20	34
DLCS_CCTV	F2	10	11
	F3	10	14
	F4	10	14
DLCS_DIM + CCTV	F2	10	49
	F3	10	40
	F4	28	40

Energy savings that the three management strategies allow obtaining with respect both to the TS and to the DLCS base cases have been assessed. These figures were not related to the whole day but specifically referred to the three limited time intervals (F2, F3 and F4). In this way, it is possible to better appreciate the influence of daylight availability during the operation time. Obviously, the time range for which the saving implies the lowest values is the F4 one, due to the scarcer daylight availability. However, saving is remarkable the same. For example, considering the DLCS_CCTV (the less profitable strategy), it ranges from 42% to 60% considering the TS. This is due also to the fact that the maximum light output of the DLCS is equal to 80% (and not to 100%) to account for the use of the maintenance factor. So, the saving will decrease over time, when the system will have to be reset and the maximum light output to be increased because of the flux emission decay. As concerns the saving referred to the DLCS, as it was previously observed, sometimes the DIM has not an effect in reducing the energy consumption (see Table 12). The highest saving is observed for the DLCS_DIM+CCTV, ranging from 10% to 49 % in F2.

It must be noted that this kind of approach can cause stress to some particular user (e.g. with a particular sensitivity of the visual system). Furthermore, it is not useful to apply it in workspaces, where tasks that require a high level of illuminance are carried out. Finally, the devices used for the described systems (i.e. luminaires able to change CCTV) are right now more expensive than the traditional ones.

4. Conclusions

In this paper, the feasibility to modulate the indoor electric loads due to artificial lighting in a possible demand-response management pattern was analyzed. To do this, three different strategies (luminous flux regulation (DIM), Correlated Colour Temperature variation (CCTV) and the aggregate of them called (DIM+CCTV) were applied to two base cases. They were: a traditional system (TS) not equipped with Daylight-Linked Control System and a daylight linked control system (DLCS). An office application has been considered. The room was studied in different orientations and facade configurations.

Results show that in all cases, it is possible to achieve a significant decrease in the absorbed power and a consequent increase in energy savings also in specific time ranges. Considering the TS, the achieved power reduction was equal to 42%, 10% and 49% considering the DIM, the CCTV and the DIM+CCTV respectively. The TS is meant to emit the same flux during the entire day, so the management strategy can be applied in whatever time range, to fulfil the electric grid requirements and reduce the power peak. Nevertheless, it must be said that when a DLCS is entailed, the power regulation due to the exploitation of the daylight represents itself a way to reduce the electric loads on the grid. However, it is not easy to predict the substance of this reduction since it strictly depends on daylight availability. For example, for the specific observed cases, the daily energy savings due to daylight use compared with the TS turned out to range from 23% (observed for a west orientation in winter with variable sky conditions) to 59% (observed for South orientation in spring with clear sky). In specific time ranges, the power reduction of the DLCS can be further reduced by applying the DIM, the CCTV and the DIM+CCTV. The reduction magnitude is different depending on the considered time range; however, for this application, they turned out to be significant even for the evening hours. For example, as for the DLCS_DIM+CCTV, they were comprised between 28% and 40% considering the 17:00-20:00 time range.

Further studies are necessary to deepen the possibilities provided by the current technologies in terms of modulation of the electric loads due to lighting. However, a first demonstration that lighting can play a significant role in the electric grid's operation has been given.

References

1. Zhu S, Luo P, Yang Y, Lu Q, Chen, Q. Optimal dispatch for grid-connecting microgrid considering shiftable and adjustable loads. In: *Industrial Electronics Society*, IECON 2017-43rd Annual Conference of the IEEE, 2017. p. 5575-5580.

2. Zizzo Z, Beccali M, Bonomolo M, Di Pietra B, Ippolito M. G, La Cascia D, Monteleone F. A feasibility study of some DSM enabling solutions in small islands: The case of Lampedusa. *Energy*, 2017, vol.140. p.1030-1046.
3. Balint A, Kazmi H. Determinants of energy flexibility in residential hot water systems. *Energy and Buildings*, 2019, vol.188. p. 286-296.
4. Khemakhem S, Rekik M, Krichen L. Optimal appliances scheduling for demand response strategy in smart home. In: *Sciences and Techniques of Automatic Control and Computer Engineering (STA);* 18th International Conference; 2018. p. 546-550.
5. Klein K, Herkel S, Henning H.M., Felsmann C. Load shifting using the heating and cooling system of an office building: Quantitative potential evaluation for different flexibility and storage options. *Applied Energy*, 2017, vol.203. p. 917-937.
6. Wang, D., Jia, H., Hou, K., Du, W., Chen, N., Wang, X., & Fan, M. (2019). Integrated demand response in district electricity-heating network considering double auction retail energy market based on demand-side energy stations. *Applied Energy*, 2019, vol. 248. p. 656-678.
7. Müller F L, Jansen B. Large-scale demonstration of precise demand response provided by residential heat pumps. *Applied Energy*, 2019, vol. 239, p. 836-845.
8. Dengiz T, Jochem P, Fichtner W. Demand response with heuristic control strategies for modulating heat pumps. *Applied Energy*, 2019, vol. 238. p. 1346-1360.
9. Xiong Y, Wang B, Chu C, Gadh R. Vehicle grid integration for demand response with mixture user model and decentralized optimization. *Applied Energy*, 2018, vol. 231. p. 481-493.
10. Diaz C, Ruiz F, Patino D. Modeling and control of water booster pressure systems as flexible loads for demand response. *Applied Energy*, 2017, vol. 204. p. 106-116.
11. Menke R, Abraham E, Parpas P, Stoianov I. Demonstrating demand response from water distribution system through pump scheduling. *Applied Energy*, 2016. vol. 170. p. 377-387.
12. Okur, Ö., Voulis, N., Heijnen, P., & Lukszo, Z.. Aggregator-mediated demand response: Minimizing imbalances caused by uncertainty of solar generation. *Applied Energy*, 2019, vol. 247. p. 426-437.
13. Ihsan, A., Jeppesen, M., & Brear, M. J.. Impact of demand response on the optimal, techno-economic performance of a hybrid, renewable energy power plant. *Applied energy*, 2019, vol. 238. p. 972-984.
14. Afzalan, M., & Jazizadeh, F. (2019). Residential loads flexibility potential for demand response using energy consumption patterns and user segments. *Applied Energy*, vol. 254. p. 113693.
15. Gomes, L., Spìnola, J., Vale, Z., Corchado, J. M.. Agent-based architecture for demand side management using real-time resources' priorities and a deterministic optimization algorithm. *Journal of cleaner production*, 2019, vol. 241, 118154.
16. https://www.casaeclima.com/ar_21616__ESTERO-Scenari-eurac-uffici-europa-INSPIRE-I-fabbisogni-energetici-degli-uffici-europei-RICERCA-.html
17. Wang Q, Xu H, Zhang F, Wang Z. Influence of color temperature on comfort and preference for LED indoor lighting. Optik-*International Journal for Light and Electron Optics*, 2017, vol. 129. p. 21-29.
18. Golasi I, Salata F, de Lieto Vollaro E, Peña-García A. Influence of lighting colour temperature on indoor thermal perception: A strategy to save energy from the HVAC installations. *Energy and Buildings,* 2019, vol. 185. p. 112-122.
19. UNI, "Illuminazione di interni con luce artificiale", UNI 10380:1999.

20. Dai Q, Huang Y, Hao L, Lin Y, Chen K. Spatial and spectral illumination design for energy-efficient circadian lighting. *Building and Environment*, 2018, vol. 146. p. 216-225.
21. Kwon S. Y., Lim J. H.Multi-objective context-adaptive natural lighting system. *Energy and Buildings*, 2017, vol. 144. p. 61-73.
22. Mariana Figueiro G, Gonzales K, Pedler D. Designing with Circadian Stimulus. available at http://www.lrc.rpi.edu/resources/newsroom/LDA_CircadianStimulus_Oct2016.pdf, [accessed 03.07.19].
23. Italian Technical Standard CEI 205-18 (2011) Guide to building automation identification of functional block diagrams and estimation of related energy savings, 1st edn. CEI, Milano
24. Directive (EU) 2018/844 of the European Parliament and of the Council of 30 May 2018 amending Directive 2010/31/EU on the energy performance of buildings and Directive 2012/27/EU on energy efficiency (Text with EEA relevance).
25. ARERA Deliberation 300/2017/R/eel, Prima apertura del mercato per il servizio di dispacciamento (MSD) alla domanda elettrica e alle unità di produzione anche da fonti rinnovabili non già abilitate nonché ai sistemi di accumulo. Istituzione di progetti pilota in vista della costituzione del testo integrato dispacciamento elettrico (TIDE) coerente con il balancing code europeo.
26. ARERA Deliberation 372/2017/R/eel, Approvazione del regolamento, predisposto da Terna S.p.a. ai sensi della deliberazione 300/2017/R/eel, relativo al progetto pilota per la partecipazione della domanda al mercato per il servizio di dispacciamento (MSD). Modifiche alla deliberazione dell'Autorità 300/2017/R/eel.
27. Konica Minolta web page – Spectroradiometer data sheet, Available at: https://www5.konicaminolta.eu/fileadmin/content/eu/Measuring_Instruments/2_Products/5_Light_and_Display_Measurement/5_Spectroradiometers/CS-2000/PDF/CS2000_EN.pdf, [accessed 03.07.19].
28. Konica Minolta web page – Illuminance meter data sheet, Available at: https://sensing.konicaminolta.us/uploads/t10a_catalog_eng-7136c91290.pdf, [accessed 03.07.19].
29. nesa web page – Illuminance sensor data sheet, Available: http://www.nesasrl.eu/media/PDF/Lux.pdf., [accessed 03.07.19].
30. nesa web page - Pyranometer data sheet, Available: http://www.nesasrl.eu/media/PDF/RSG1.pdf., [accessed 03.07.19].
31. EN,"Light and lighting - Lighting of work places - Part 1: Indoor work places", 12464-1:2011.
32. Bellia L, Fragliasso F. New parameters to evaluate the capability of a daylight-linked control system in complementing daylight, *Building and Environment*, 2017, vol. 123. p. 223-242.
33. Dialux website: www.dial.de/en/dialux [accessed 03.07.19].
34. J. Mardaljevic, M. Andersen, N. Roy, and J. Christoffersen, *Daylighting metrics for residential buildings*, in 27th Session of the CIE, Sun City, South Africa, 9-16 July 2011.