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Analisys on the feasibility to modulate lighting systems load: the case study of Palermo

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***Abstract*—The feasibility to shift and/or modulating the loads that characterize buildings can be useful to improve the performance of smart grids. As known, it is not possible to shift in the time the operating time of the lighting system, but it is possible to modulate the needed electric power. In this paper, the first set of data and a preliminary analysis conducted in the Solarlab of the University of Palermo are presented. The innovative lighting system was designed, sized and installed with the aim of evaluating the consumption of an island user that can be controlled by the DSO or an aggregator. In order to do this, the lighting system load was modulated by applying different strategies: varying the Correlated Colour Temperature (CCT), varying the luminous flux, and applying a daylight-linked control system (DLCs). The measurements were taken and also provided useful data to evaluate the real performance of the lighting system and the DLCs. Furthermore, the study focused the attention on the visual comfort parameters. First measurements analysis shows that the strategies applied are useful to modulate the absorbed power and, consequently to be managed and controlled by an aggregator. A variation of absorbed power of the 30% can be achieved by varying the CCT from 3000K to 6000K.**

Keywords—Lighting, Correlated Colour Temperature, Smart Grid, aggregator

I. INTRODUCTION

Electricity production was dependent for a too long time on the availability of fossil fuels such as gas, oil, and coal. Climate change problems are changing this course by improving the distribution of renewable sources, especially solar ones. They are often coupled by distributed generation (DG). It plays a fundamental role in the development of sustainable cities and societies [1] and changed the management and behaviour of the power grid that is becoming a smart grid [2]. One of the strategies widely applied in demand-side management is to shift the loads of buildings [3]. Indeed, consumption profiles can be adapted to generation profiles which can be posed as an optimization problem [4]. Even if, as affirmed by [5] nowadays, the potential to shift load from peak to off-peak is limited. In his review, Siano [6] explained that advanced DR programs and innovative enabling technologies are required for such applications and to support the coordination of DR in smart grids [7].

In general, shiftability can be applied to loads such as specific devices (e.g. washing machines) or other buildings plants (e.g. HVAC systems [8]). Not all the loads that characterize the buildings sector can be shifted in the operating time. Indeed, the lighting system has to be used to carry out tasks at a specific moment of the day. In general, in order to reduce the peak, the activities related to the lighting system are the substitution of light sources [1]. It makes the lighting load fixed. In [9], the authors evaluated the possibility to modulate indoor artificial lighting to support this reduction. In this study, the topic is investigated more in detail this topic. Indeed, the measurement campaign was performed in a laboratory room, equipped as an office, but for real scenarios. Furthermore, in this paper visual comfort condition was considered.

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II. STRATEGIES AND METHODOLOGY

The plant has the purpose of emulating the behaviour of an island user (domestic or tertiary) who receives control signals from the distribution system operator (DSO) or an aggregator. In this regard, as said, since the possibility of shifting the load given by the lighting system is not suitable for obvious practical reasons, the possibility of modulating the load of the internal artificial lighting to further contribute to the reduction of consumption was investigated. To this end, different strategies were applied: the variation of the CCT (favouring a decrease in the absorbed power in the event that action is taken by varying the CCT from hot to cold) and the luminous flux of the lighting system installed. At the same time, the impact of a DLCS was evaluated. Furthermore, the test was used to evaluate the real performance of the lighting and control system in terms of energy saving and visual comfort.

The operation of the lighting system in different operating conditions, in order to quantify the energy savings due to the application of each selected management strategy, was tested. In particular, the tested scenarios took into consideration different modulation time periods (chosen as the period often adopted in the time tariff schemes by electricity suppliers), different end uses (residential and tertiary) considering different horizontal illuminances depending on the type of task and various strategies including:

- strategy A: variation of horizontal illuminance;
- strategy B: variation of CCT;
- strategy C: variation of CCT and a lowering of the luminous flux (FL) emitted by the sources and, consequently, of the illumination on the workplane were considered;

• strategy D: variation of CCT and the use of the Daylight-linked control;

• strategy E: variation of CCT and a lowering of the luminous flux (FL) emitted by the sources and, consequently, of the illumination on the workplane and the use of the Daylight-linked control system.

Regarding strategy C, the measured data were analysed by varying the CCT of the sources as applied for strategy B. In this case, as described, a variation of the luminous flux and a consequent variation of the illuminance on the plane was also applied (from 500 to 400 lx, in the "office" case and from 300 to 200 lx in the "residential" case).

III. EXPERIMENTAL SETUP

The innovative lighting system is installed in the Solar Laboratory of the Engineering Department of the University of Palermo (latitude 38 ° 6'43 "56 N, Longitude 13 ° 20'11" 76 E) [10]. The laboratory (Fig. 1) has a roughly rectangular plan and, along with one of the two long sides, there are 4 windows facing southeast which provide a high contribution of daylight. During the morning hours, the solar radiation is direct, while during the second part of the day the contribution of daylight is given by diffused radiation.

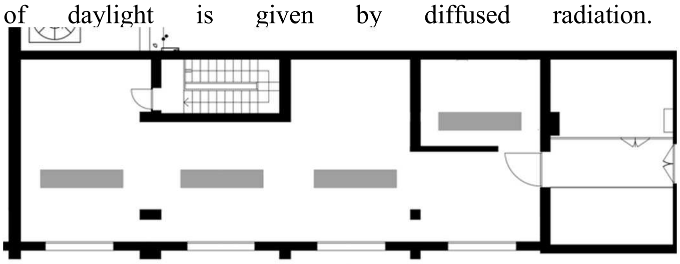

Fig. 1. Plan of the laboratory with the positioning of the lighting fixtures..

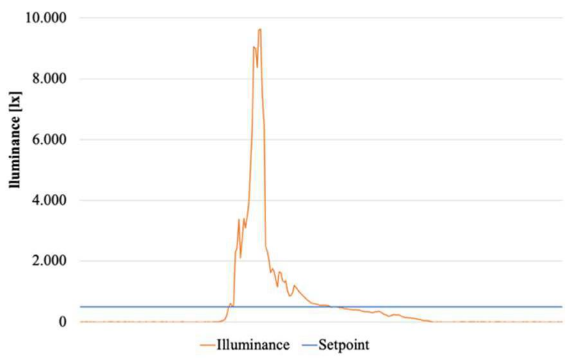

Fig. 2. Illuminance values measured with the contribution of daylight during a day characterized by clear sky.

As can be seen from the measurements shown in the graph in Fig. 2, taken during a day characterized by clear sky, it is possible to reach lighting levels of about 10,000 lx in the winter season. The system consists of:

• n.4 suspensions LED with microprismatic optic;

• 1 central controller for automation;

• APP to control artificial lighting according to the amount of daylight;

• APP to generate dynamic scenes/sequences linked to schedules or at the time of activation;

• n. 1 photosensor to detect daylight.

The laboratory was set up in order to simulate both an office and a residential that was used as case studies. For each of the two case studies, the operation of the lighting system in different operating conditions was analysed in the laboratory. Furthermore, two basic cases of the lighting system were considered: with and without DLCs. For the first case, the sensor was installed on the ceiling to detect incident daylight from windows. The LED pendant luminaires chosen have a tunable white LED source, according to the aims of this research, and microprismatic optics. The power used is about 57 W and each fixture is designed to be controlled via the DALI protocol. The luminaires are characterized by a maximum luminous flux of 5500 lm and a luminous efficiency of> 110 lm / W. The colour rendering is> 90 and the CCT (tunable) can vary in a range ranging from 2700 K to 6500 K (Fig. 3). The MPO-plus optic with multi-layered micro-pyramids allows to have a UGR index <19 in this case as well. The central controller can be programmed to control the lighting system based on time, interval, attendance or daylight or via manual control. Also in this case, the lighting system was sized in order to reach the lighting levels suggested by the technical standards [11] to carry out activities related to two end uses: office (worst case) and residential case. The lighting design was supported by simulations carried out using the DIALux software.

Fig. 3. Pictures of luminaires with different CCT.

The four perimeter walls of the room chosen to carry out the tests are characterized by a reflectance factor of 90%. The ceiling and floor are characterized by reflectance factors of approximately 85% and 40% respectively. The luminaires were connected to a DALI control unit, which allows not only to vary the CCT, but also to adjust the luminous flux from a maximum value (indicated by the touch panel as 100%) to a minimum (indicated by the touch panel as 1%) also via the app.

The first measurements in the laboratory were carried out considering five different levels of luminous flux (LFL): 100%, 75%, 50%, 25% and 1%. For each level, the CCT varied from 2700K to 6500K. For each combination of luminous flux variation and CCT, the power consumption was measured by using an electronic power meter.

A. *Measurement instrumentation*

As said, the lighting system was controlled by a photosensor installed on the ceiling. Unfortunately, this kind of sensor cannot provide a series of collected data. It measures the illuminance value due to the contribution of daylight and sends the data to the system to the ballast which adjusts the luminous flux of the lamps based on it.

Delta Ohm HD2021T sensors (Fig. 4) and a Siemens Sectron PAC3200 data logger were used for the measurement campaign. Data were collected by using a Labview interface. One of the lux meters was installed near the photosensor used to control the luminaires. The latter provided useful measures to verify the correspondence between the measurements detected by the DLCs control system and the measurements detected by the lux meters used to detect the illuminance measurements.

Fig. 4. Delta Ohm sensors used for the measurement of illuminances.

Two other lux meters installed respectively on another workplane and in another point of the ceiling will be useful measures to further test the performance of the system. Indeed, the simplified systems provide for the positioning of a single sensor on the ceiling to control several lamps. In the case study object of this document, there are 2 lamps on the workplanes, but we focused first and foremost on the calibration of the photosensor placed in correspondence with a single workplane. To do this, during the photosensor calibration phase the values were indicated on the surface, with the lamps switched on at 100% and off, placed in correspondence with the workplane.

IV. MEASUREMENT CAMPAIGN

The measurement campaign was carried out during three months of the winter season. The first measurements in the laboratory were made considering nine different levels of luminous flux to perform the measurements: 100%, 90%, 80%, 70%, 60%, 50%, 40%, 30% and 20%. Using an electronic power meter, the corresponding power at six different CCTs (2700K, 3000K, 4000K, 5000K, 6000K, 6500K) was measured for each level of luminous flux listed above. The varying of luminous flux and CCT was possible thanks to the app (Fig. 5)

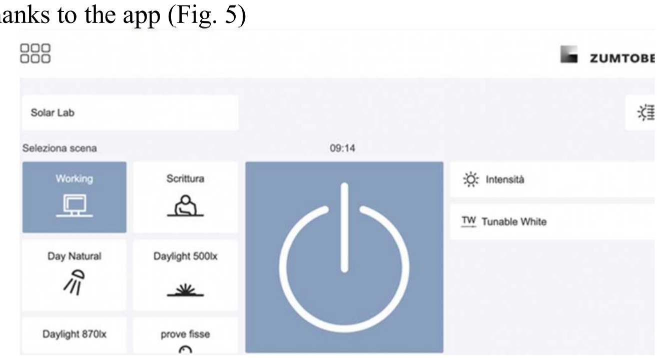

Fig. 5. Screenshot of the main page of the app used to set the scenarios and to vary the luminous flux and the CCT.

In order to take the lighting and electrical measures, the instrumentation described in section III was used.

The graph below shows the measurements of absorbed power measured at each variation in luminous flux and each CCT. From these first measurements, it was found that the absorbed power varies by only about 1% by varying the CCT from 5000 K to 6000 K. The differences with the measurements relating to a CCT equal to 6500 K are more negligible. This is shown in Fig. 6 where the measures were plotted.

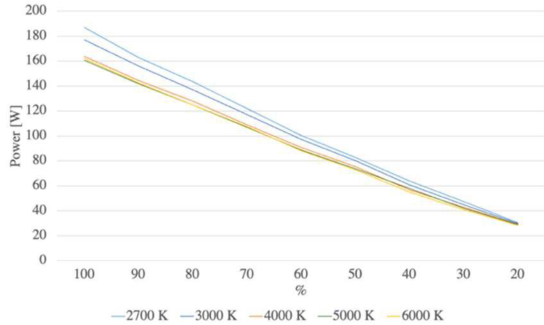

Fig. 6. Measurements of absorbed power measured at each variation in luminous flux and each CCT.

The lines, each of which corresponds to a different CCT, are ever closer and converging towards a single point. This means that as the CCT increases, the progressive reduction of the absorbed power decreases and becomes less and less significant. Although, as will be shown, different combinations of CCT and illuminance values were considered, attention was paid to the situations of illuminance and CCT that guarantee visual comfort.

For this, reference was made to the Kruithof diagram (Fig. 7). The Kruithof [12] curve appears as a Cartesian graph between illuminance and CCT and provides indications of the visual comfort that can be obtained with a given light source.

The area within the two curves empirically represent comfortable conditions for the human eye, while the external ones represents conditions of discomfort. It, therefore, indicates the visual comfort region by associating the lux values on the ordinate axis with those of CCT on the abscissa axis. The colour sensation given by particular lighting conditions can vary with the perceived brightness. This happens because the rods and cones responsible for photopic and scotopic vision respectively are active simultaneously in the eye, each with specific colour curves. In particular, the function of the rods gradually takes over from that of the cones as the brightness of the scene is reduced [13].

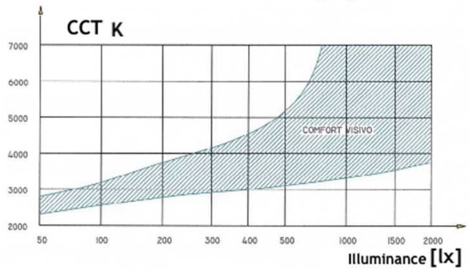

Fig. 7. Kruithof curve.

The time intervals considered were selected based on the high price of electricity and other periods of about three hours, during which a load aggregator may require a reduction in the electrical load, for the office case, were considered and in particular:

- Phase I: 11: 00-14: 00;
- Phase II: 14: 00-17: 00;
- Phase III: 17: 00-20: 00.

For the residential case, the following daily phases were considered:

• Phase I: 07: 00-09: 00;
• Phase II: 18: 00-20: 00;
• Phase III: 20: 00-22: 00.

In order to conduct the analysis related to the strategies D and E, a second measurement campaign was performed. In particular, the measures were taken for about a month-long period by applying the DLCs for office and residential cases.

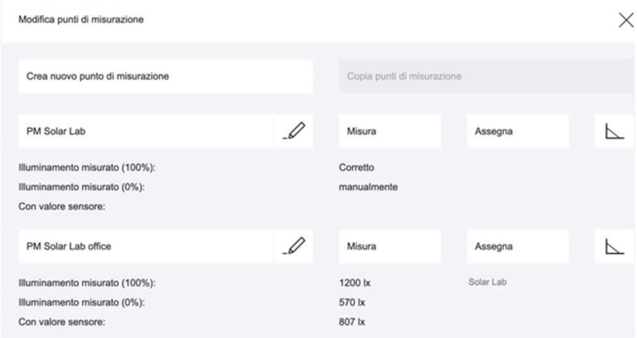

Fig. 8. Screenshot of the app.

Through the app, it was also possible to configure the photosensor (Fig. 8) in order to achieve the desired illuminance on the work surface depending on the final use case (office/residential case).

V. RESULTS

The measurements taken were compared and analysed for the base cases and in presence of the control strategies. Table I below shows the absorbed power measured at each variation in the luminous flux and for each CCT.

TABLE I. MEASUREMENTS OF ABSORBED POWER MEASURED AT EACH VARIATION IN LUMINOUS FLUX AND EACH CCT.

	CCT [K]				
Percentage of absorbed power [%]	***2700***	***3000***	***4000***	***5000***	***6000***
100	187	177	164	160	162
90	163	156	144	142	143
80	143,6	137	128	125	125
70	122	117	109	107	107
60	100,4	97	91	89	88
50	82,8	80	75	74	73
40	64	60	57	58	55,1
30	47,5	45	43	42	41
20	30,4	30	29	29	28

Based on the Kruithof curve, the power values corresponding to the CCT and illuminance values on the workplane were identified, falling within the portion of the graph that identifies comfort situations.

As can be seen from Table II, this first analysis did not take into account the illuminance values associated with certain visual tasks related to the final uses selected to conduct the analyses object of this study. The table below shows the values of absorbed power, illuminance on the workplane, percentage of absorbed power and CCT. The measurements were taken, obviously, in the absence of daylight.

TABLE II. MEASUREMENTS OF ABSORBED POWER MEASURED AT EACH VARIATION IN LUMINOUS FLUX AND EACH CCT.

CCT	**Illuminance [lx]**	**Power [W]**	**Percentage of absorbed power**
3000 K	620	181	100%
	500	141	80%
	440	120	70%
	380	100	60%
	320	83	50%
	260	62	40%
4000 K	500	131	80%
	380	93	60%
	450	112	70%
	330	78	50%
	635	167	100%
	265	59	40%
5000 K	266	58	40%
	335	76	50%
	390	91	60%
	450	110	70%
	520	127	80%
	640	164	100%
6000 K	644	165	100%
	520	128	80%
	450	110	70%
	390	91	60%
	338	75	50%
	260	57	40%

Starting from these measures, it was possible to calculate the daily consumption and saving achievable by adopting the strategy that foresees the variation of the CCT and those achievable by decreasing the luminous flux (Fig. 9 and Fig. 10).

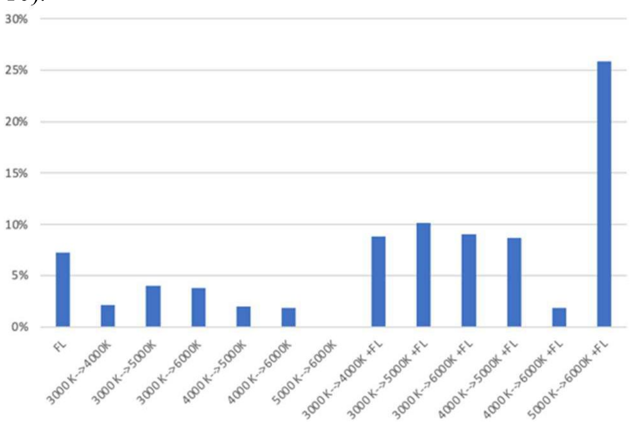

Fig. 9. Percentage of saving achiavable by applying strategies in office case.

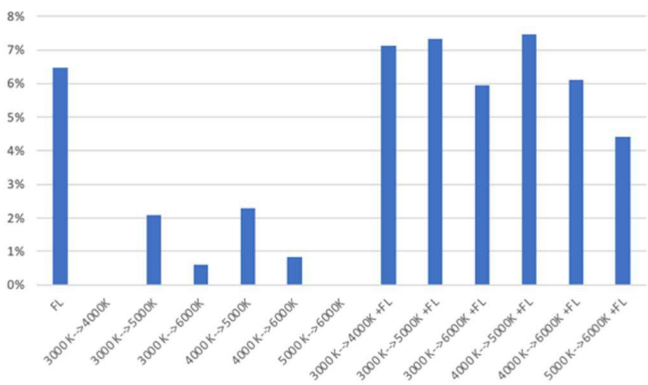

Fig. 10. Percentage of saving achiavable by applying strategies in residnetial case.

As can be seen, the application of strategies A and B in the residential case have a greater impact on reducing the electrical load than strategies C and D.

It is necessary to underline that the case study used is composed of a single room and reduced installed power. Therefore, the reduction of the load associated with the power absorbed by the lighting system is proportional to the scale of the case study. In order to apply the control strategies aimed at the aforementioned purpose to a real case study related to one or more buildings, the percentages would be proportionate and therefore far greater. During some days when the weather conditions, and consequently the contribution of daylight, was particularly variable, the DLCs system responded in a non-linear way due to the variation of the highly variable daylight contribution. This affected the consumption detected as the continuous switching on and off resulted in unnecessary excesses of illuminance [14]. The operation of the plant is based on an occupancy schedule involving the 09:00-20:00 time slot for the final "office" use and on an occupancy schedule from 07: 00 to 08:00 and from 19:00 to 23:00 for the final use "residential". In this latter case, the switching on and off of the system was variable in order to simulate residential use as much as realistically, which tends to be more varied and labile than in the "office" case study. The saving achievable by applying strategies A and B are shown in Table III.

TABLE III. COMSUPTION AND SAVING ACHIEVABLE IN OFFICE CASE.

Strategy	Variated parameter	Consump. (base case) [Wh]	Power reduct.	Consump. (strategy) [Wh]	Daily saving
A	FL	1310	24,0%	1216	7,2%
B	3k K-->4k K	1410	7,1%	1380	2,1%
	3k K-->5k K		13,3%	1354	4,0%
	3k K-->6k K		12,7%	1356	3,8%
	4k K-->5k K	1310	6,7%	1284	2,0%
	4k K-->6k K		6,0%	1286	1,8%
	5k K-->6k K	1222	-	1225	-
C	3k K-->4k K+FL	1410	29,4%	1286	8,8%
	3k K-->5k K+FL		33,8%	1267	10,1%
	3 K-->6k K+FL		30,2%	1282	9,1%
	4k K-->5k K+FL	1310	28,8%	1197	8,6%
	4k K-->6k K+FL		24,8%	1286	1,8%
	5k K-->6k K+FL	1222	19,4%	906	25,8%

Obviously, the greatest reduction in absorbed power (30%) would occur by varying the CCT from 3000 K to 6000 K. However, this strategy does not appear to comply with the indications of comfort conditions reported in the Kruithof curve.

The table below shows the daily consumption and reductions of absorbed power with the consequent savings achievable by adopting strategies A, B and C.

TABLE IV. COMSUPTION AND SAVING ACHIEVABLE BY APPLYING STRATEGIES IN RESIDENTIAL CASE.

Strat	Variated parameter	Cons.(base case) [Wh]	Power reduct.	Cons.. (strategy) [Wh]	Daily saving
A	FL	467	38,7%	437	6,5%
B	3k K-->4k K	467	-	468	-
	3k K-->5k K		12,5%	457	2,1%
	3k K-->6k K		3,6%	464	0,6%
	4k K-->5k K	473	13,7%	463	2,3%
	4k K-->6k K		4,9%	469	0,8%
	5k K-->6k K	408	-	415	-
C	3k K-->4k K+FL	467	42,8%	434	7,1%
	3k K-->5kK +FL		44,0%	433	7,3%
	3k K-->6k K +FL		35,7%	439	6,0%
	4k K-->5k K +FL	473	44,7%	438	7,5%
	4k K-->6k K +FL		36,6%	444	6,1%
	5k K-->6k K +FL	408	26,5%	390	4,4%

Strategies D and E envisaged the application of the DLCS system. As described above, in the first case only the variation of the CCT was applied. In the second case, the possibility of varying the luminous flux and consequently decreasing the horizontal illuminance on the workplane was analysed. In both cases, the application of the DLCS certainly had a positive impact on the absorbed powers.

In a first step, the measurements were monitored (examples are reported in Fig. 11 and Fig. 12) in order to test the DLCS system and the app used to program the scenarios. While not useful measures for the analyses aimed at the purpose of this paper, some useful observations are provided below. It was noted that during some days in which the weather conditions, and consequently the contribution of daylight, was particularly variable, the DLCs system responded in a very linear way due to the variation of the highly variable daylight contribution. As said, this affected the consumption detected as the continuous switching on and off resulted in unnecessary excesses of illuminance.

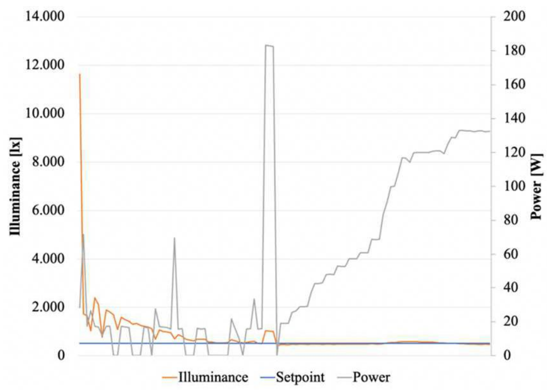

Fig. 11. Sample of illuminance and power measured during a very variable day.

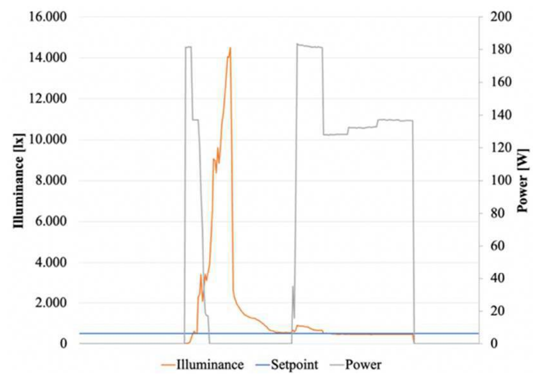

Fig. 12. Sample of illuminance and power measured during a sunny day.

The case shown in Fig. 12 refers to the application of the CCT variation in time phase II. Comparing the consumption detected by applying the strategies, this appears to be the most advantageous range (table V). Indeed, the consumption measured by applying strategy D is around 1400 Wh. By applying the reduction of strategy E, consumption could be reduced to 1225 Wh. However, it must be noted that this consumption is calculated based on the measures shown in Table II and not measured. Therefore, they do not take into account the aforementioned malfunctions.

From the first measurements taken by applying the DLCs system to the "residential" case, it was possible to note that it is less convenient to install the aforementioned systems as usually the lighting system, based on the occupancy schedules considered, is used at times of the day when the contribution of daylight. This is since the lighting system would switch on at maximum absorbed power for most of the time. The application of strategies D and E results were very different because they were largely influenced by the contribution of daylight and are therefore largely variable depending on whether they refer to sunny, variable or cloudy days. In this regard, it is essential to remember that the measurements were taken during the winter season. By applying strategy D, in the office case the reduction of absorbed, power ranged:

- from 16% to 57% compared with the basic case without DLCs use and just around 1% compared with the application of DLCs for the phase I;
- from 16% to 58% compared with the basic case without DLCs use and from 0.4% to 2.6% compared with the application of DLCs for the phase II;
- from 17% to 59% compared with the basic case without DLCs use and from 32% to 65% compared with the application of DLCs for the phase III.

By applying strategy E, in the office case the reduction of absorbed, power ranged:

- from 20% to 58% compared with the basic case without DLCs use and just around 1% compared with the application of DLCs for the phase I;
- from 0.5% to 6.5% compared with the basic case without DLCs use and from 1.9% to 3.9% compared with the application of DLCs for the phase II;
- from 38% to 68% compared with the basic case without DLCs use and from 11% to 26% compared with the application of DLCs for the phase III.

VI. CONCLUSION

In this paper, the first data and analysis conducted in the Solarlab of the University of Palermo setup are presented. The innovative lighting system was designed, sized and installed to evaluate the consumption of an island user that can be controlled by the network manager or an aggregator. First measurements analysis shows that the strategies applied are useful to modulate the absorbed power and, consequently to be managed and controlled by an aggregator. A variation of absorbed power of 33.8% can be achieved by varying the CCT from 4000K to 5000K and applying a reduction of horizontal illuminance for the office case. A variation of absorbed power of 44.7% can be achieved by varying the CCT from 3000K to 5000K and applying a reduction of horizontal illuminance for the residential case. The application of the strategy in the case when DLCs is installed appears to be useful by applying the strategy during phase III in both cases. It is because, in general, thanks to the application of DLCs, during the morning time the luminaires are switched off.

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