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RESEARCH ARTICLE

Applications of Hybrid Solar Streetlamps: Electrical Performance Measurements and Development of Algorithms for Their Optimal Management

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ABSTRACT This study examines the electrical performance and management of hybrid solar street lighting systems with the objective of optimizing their operation for sustainable urban development. Hybrid solar streetlights, which integrate photovoltaic panels with additional power sources, offer resilience and reliability that are crucial for urban settings. A hybrid solar streetlamp was installed in a city in central Italy and monitored for over a year to analyze its electrical behavior and the illuminances obtainable under different boundary conditions and operational programs. The measured data permit the development of an optimization algorithm in a Python program for the optimal management of the solar streetlamp and the forecasting of the battery charging/discharging cycles, as well as the electricity taken from the grid. The simulation scenarios permit the development of a novel management algorithm that is capable of optimizing the battery usage with a minimal draw on the grid in order to achieve a state of near self-sufficiency for the solar streetlamp. The results demonstrate that tilted solar panels enhance energy production, while optimized LED power profiles and system management enhance efficiency. The study highlights the importance of maintaining the state of charge (SOC) of the battery above 20% to extend its lifetime and reduce replacement needs. Economic analysis indicates significant potential energy savings, emphasizing the necessity of system optimization for economic viability and environmental sustainability in urban lighting. Despite initial investment costs and challenges, adopting hybrid solar lighting in urban environments presents substantial benefits, paving the way for a more sustainable and energy-efficient urban future.

INDEX TERMS Electricity consumptions, hybrid solar streetlamp, LED, modeling, optimization algorithm, photovoltaic (PV), storage.

I. INTRODUCTION

The term "sustainability" has its origins in the landmark Brundtland Report, officially titled "Our Common Future", released by the United Nations World Commission on Environment and Development in 1987. Coined after the Commission's chair, Gro Harlem Brundtland, the report defined sustainable development as "development that meets the needs of the present without compromising

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the ability of future generations to meet their own needs'' [1].

Since the publication of the Brundtland report, which occurred almost four decades ago, the concept of sustainability has remained a central topic of political discourse. This discourse has emphasized the interconnectivity between the environment and our socio-economic system. However, it would appear that the number of actions that have been undertaken is always insufficient to ensure the future of our children. Nevertheless, in the context of prevailing pessimism about the future, Hannah Ritchie, data analyst and lead researcher at Our World in Data, offers a refreshing perspective by suggesting that that ''we have the opportunity to be the first generation that leaves the environment in a better state than we found it'' and that ''the world has never been sustainable.'' Consequently, the goal of sustainability has never been achieved before [2]. That is because we have never achieved both halves of the equation expressed by the Brundtland report: protecting the environment and meeting the needs of every human on Earth.

In order to address these challenges and ensure a sustainable future, it is imperative that a fundamental shift in our approach to urban development be implemented. A radical transformation of the urban environment is required. Cities must be reimagined as resilient and regenerative hubs that prioritize human well-being while respecting the limits of the planet. However, the most crucial aspect is the necessity for collective action to achieve a goal that has never been achieved before.

Urban areas are distinguished by a high energy demand and limited space, presenting both challenges and opportunities for innovation and sustainability. In this context, solar energy emerges as a promising solution for powering urban infrastructure, with particular emphasis on innovative designs and enhancements to solar cell efficiency [3].

Street lighting is one of the fundamental social services that defines urbanized areas. It can account for a 15% to 40% of total electricity demand in cities, and for approximately 3% globally [4], [5]. Consequently, the advent of innovative lighting systems, which are also feasible due to the highly efficient last generation LED technologies [6], could simultaneously enhance the quality of life for individuals, particularly those residing in disadvantaged areas with inadequate lighting [7], while also reducing the carbon footprint of urbanized areas. Solar streetlights represent a sustainable alternative to traditional grid-powered lighting systems. These streetlamps are typically divided into two main categories: standalone solar streetlights and hybrid solar streetlights. Standalone or off-grid solar streetlights rely solely on solar energy captured by photovoltaic panels during the day to illuminate streets at night. While these streetlights have been widely and successfully installed in areas with consistent sunlight [8], [9], they have brought a highly positive impact in remote and rural areas without access to electricity [10]. However, they may experience limitations in urban environments where weather conditions and shading from buildings can impact solar energy generation. These aspects constitute barriers to their installation.

In contrast, hybrid solar streetlights integrate photovoltaic panels with additional power sources, such as grid electricity or other types of sources, such as fuel cells or wind turbines [11], [12], [13]. This hybrid approach, particularly when not reliant on an intermittent energy source, allows for enhanced reliability and resilience, especially in urban settings where uninterrupted lighting is essential for ensuring the safety of drivers and pedestrians. Moreover, the integration of solar technology into public spaces serves to promote awareness of sustainable energy practices, fostering community engagement and a sense of collective responsibility [3]. This underscores the pivotal role of local administration in driving the transition toward decentralized energy systems, thereby enabling communities to actively engage in the benefits derived from local projects [14]. Interesting research studies concerning this kind of solar streetlamp was conducted by Belloni et al. [15], [16], [17], [18]: in [17] authors analyzed the electricity parameters and the lighting behavior of a photovoltaic (PV)-integrated lighting system installed along a footpath and monitored for several months. Additionally, data were employed to investigate the potential substitution of the conventional lampposts along the walkway with the novel proposed system. A technical-economic analysis was conducted to evaluate the efficacy of this solution in terms of both electricity consumption reduction and cost savings.

In this context, the present study aims to analyze the performance and application of an innovative hybrid urban lighting system with integrated photovoltaic panels and grid connection as backup. The current and voltage of the panel, current and voltage of the lamp, current outgoing and incoming from the battery, and the AC current taken from the grid were measured for approximately one year under a variety of operational profiles. The data were utilized to validate an algorithm capable of simulating the behavior of the streetlamp in different settings. The final objective is not only to maintain a minimum energy draw from the grid and to allow the best illuminance conditions on the road, but also to preserve the battery in the optimal state-of-charge (SOC) range.

The combination of solar energy with conventional electricity sources addresses the unpredictability of renewable energy generation, thereby extending the use of solar lighting beyond rural areas to urban environments. The integration of hybrid power systems enhances reliability and resilience, rendering it an optimal solution for urban lighting, where consistent illumination is of paramount importance for safety considerations.

II. MATERIALS AND METHODS

A. THE CASE STUDY

The solar-based streetlamp under consideration in this study is composed of a PV panel integrated into the rear surface of the lamp. The pane with PV cells on the front side and

LEDs on the back side can be manually oriented to a specific tilt angle of the PV panel. The lamp/PV structure is mounted on an aluminum pole with a total diameter of 0.08 m and a total height of 4 m. The total weight of the system is approximately 18 kg. The total peak power of the PV system is 80 W, and it is composed of monocrystalline cells with a total efficiency exceeding 19%. The LED has a power of 80W, a luminous flux of 13795 lm, an efficiency of the lamp of 172.5 lm/W, and an expected lifetime of greater than 50000 hours. The lamp's power can be adjusted via an intelligent control system. This allows for the implementation of different working modes, which can be tailored to suit the changing seasons and environmental conditions. In addition to that, the lamp can be dimmed to the desired percentage of the maximum power by a remote controller. The SR-EH120 series PWM controller integrates several functions, including the management of solar charging and discharging, the management of lithium batteries, the LED boost constant current drive, and the intelligent control of switching between battery power and AC power for load. Pulse width modulation (PWM) is employed for the purpose of charging batteries, including both lead-acid and lithium batteries. The battery type may be selected via the remote control. In the case of a lithium battery, the controller will adopt a two-stage charging process as shown in Fig.1.

The storage system comprises a solar charge controller, a terminal block circuit, a battery management system (BMS), and a lithium-based battery ($LiFePO_4$, 560 Wh) located on the rear side of the panel. This battery has a lifespan that can vary from 2000 up to 10000 cycles, depending on its depth of discharge (DOD, %). The operational time of the streetlamp is determined by solar radiation, indirectly measured by the photovoltaic voltage values. A threshold of 5V has been set by the remote control. When the PV voltage drops below 5V, the lamp turns on, whereas, when the voltage exceeds 5V, the lamp turns off. Additionally, a microwave proximity sensor has been incorporated to detect passing vehicles or pedestrians, giving the option to activate the lamp only if motion is detected.

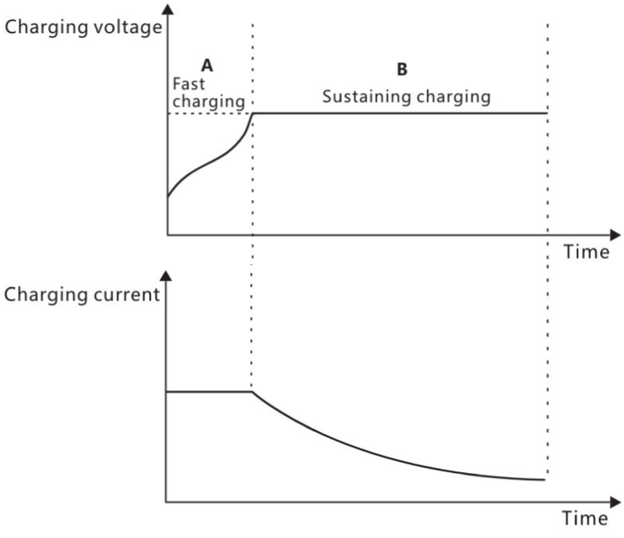


FIGURE 1. **Charging curves for voltage and current for the lithium-based battery management.**

FIGURE 2. **View of the solar streetlamp installed in the experimental site: a) from the bottom view of the LED lamp; b) from the top, view of the PV panel.**

The PV system generates electricity, which is used to recharge the battery during the day. During the night, when the lamp is on, the battery supplies the electricity to the LED. When the battery is almost discharged, the energy for supplying the load is taken from the grid. In this instance, it is necessary to convert the alternating current (AC) to direct current (DC) by means of an inverter integrated in the panel. The streetlamp was installed in April 2023 in a site located near the University of Perugia (Engineering Department) in Italy central region. For this first analysis, measurements were made with the device programmed to operate at its maximum power. Fig.2 shows some photos of the experimental field.

B. ELECTRICAL PERFORMANCE MEASUREMENTS

The electric parameters were quantified by a digital precision multimeter [19], which was capable of measuring volts, ohms, and ampere. The meter exhibited basic AC voltage accuracy of up to 0.0024%, a 10 A current range, and a wide Ohms range. Furthermore, the device is employed for the purpose of recording frequency and period. In the present experimental analysis, both the voltage of the grid and the current taken from the grid have been measured with a time-step of one minute. The system is also connected to a PC for the monitoring of data trends. The program is Fluke View Forms Basics, and the graphical display modes include the Trendplot™paperless recorder, as well as statistical and histogram displays of the data. In Fig.3, the principal components of the photovoltaic-based lighting system are presented, accompanied by a scheme of the measurement system chain.

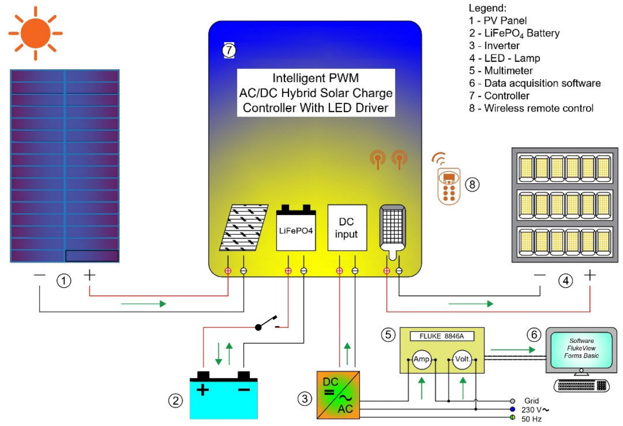


FIGURE 3. Main components of the PC-based streetlamp and the measurement apparatus installed for the monitoring.

C. ENVIRONMENTAL MEASUREMENTS AND LIGHTING MODEL

Based on the photometric data provided by manufacturer, it was possible to develop a lighting model in *Relux*®software [20] and to compare the luminance values with the Reference Standard ones, which are minimum values to be guaranteed in each road category (see Section IV).

Furthermore, the environmental parameters were also monitored during the reference period, April 2023 to April 2024. In particular, the global solar radiation on horizontal surfaces, the outdoor temperatures, and the wind speed are recorded by a weather station situated in a site near to the experimental field. The mean global solar radiation data were found to be correlated with the productivity of the panel.

D. MANAGEMENT PROFILE OF THE STREETLAMP

The default settings of the system's parameters consist of a LED power derating algorithm based on battery state of charge. Fig.4 illustrates three distinct derating profiles that can be configured based on battery voltage levels and desired runtime. However, for the purposes of this initial analysis, the above-mentioned power modulation profiles were excluded, as the final power output (3% of the nominal power) was deemed insufficient to meet the requisite standards for road lighting quality. Nevertheless, it should be noted that user-defined modulating profiles can be set to tailor the system's performance to the required specifications and will be considered in the next steps analysis. Motion detection mode was also deactivated, so that the lamp could stay on for the whole night period.

Two distinct LED power schedules were examined: one maintaining illumination consistently at 100%, and another simulating time-based standalone light control achievable with last generation street lighting technologies, which allow for a reduction in LED power by 30% post-virtual midnight, the halfway time between sunset and sunrise.

The system is not equipped with an astral clock, but the on-off schedule is controlled by PV voltage values. Consequently, power was reduced to 70% after the time range proposed in Table 1, which was estimated by considering the median values of dusk and dawn time for each season. The schedule may be configured through the controlling platform by installing the IoT (Internet-of-Things) module provided by the manufacturer.

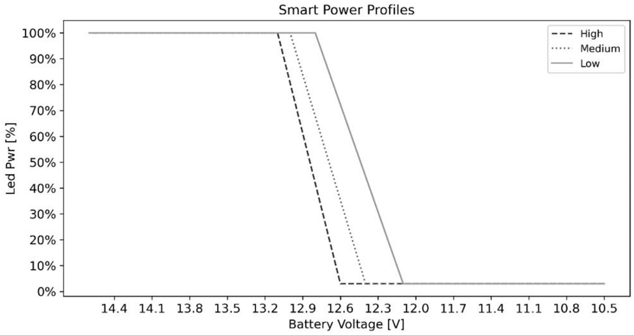


FIGURE 4. LED power derating profiles depending on battery voltage. The "High" profile ensures a higher battery duration time.

TABLE 1. Time range until LED power diminishes to 70% of initial intensity.

Season	Time range at 100%(h)	Time range at 70%(h)
Winter	7	7
Spring	6	5
Summer	5	4
Autumn	5	6

E. SIMULATION ALGORITHM DESCRIPTION

The algorithm underlying this study was developed using the Python library, *pvlib*, which is renowned for its robust capabilities in solar energy analysis [21]. The incorporation of the framework's inherent capabilities facilitated the usage of locally measured radiation data, thereby ensuring a comprehensive assessment of photovoltaic panel producibility.

Measured radiation database only included global horizontal irradiance (GHI). Therefore, after a preprocessing stage, direct normal irradiance (DNI) and direct horizontal irradiance (DHI) were derived using the *Erbs* model [22], which estimates the diffuse fraction DF from GHI through an empirical relationship between DF and the ratio of GHI to extraterrestrial irradiance. The function employs the diffuse fraction to compute DHI as follows:

$$DHI = DF \cdot GHI \tag{1}$$

Then DNI can be estimated from equation (2), where θ_z represents the solar zenith angle, calculated considering local coordinates and declination angle through datetime.

$$GHI = DNI \cdot cos\theta_z + DHI \tag{2}$$

Once the three radiation components were obtained, the incident solar radiation on the PV panel surface, also known as plane of array (POA), was calculated for a given tilt angle β and angle of incidence AOI to assess PV production.

$$POA = DNI \cdot \frac{cos\,(AOI)}{cos\theta_z} + DHI \cdot \frac{1 + cos\beta}{2} + \rho_p \cdot GHI \cdot \frac{1 - cos\beta}{2} \tag{3}$$

where ρ_p is the asphalt surface albedo, considered equal to 0.1 as a mean value between freshly paved asphalt and aged one [23].

The nominal peak power of the photovoltaic system is established at standard test conditions (STC) of 1000 W/m^2 irradiance, air mass of 1.5, and cell temperature of 25 °C. Eq. (4) allows to determine the actual DC power output of the PV system based on the ambient air temperature and the plane-of-array (POA) irradiance.

$$P_{dc} = \frac{POA}{1000} P_{dc0} \left[1 + \gamma_{pdc}\left(T_{cell} - T_{ref}\right)\right] \tag{4}$$

where P_{dc0} is the nominal power, γ_{pdc} is the temperature coefficient, and T_{cell} is the solar module temperature, estimated by using the Faiman model [17].

$$T_m = T_a + \frac{POA}{U_0 + U_1 \cdot W_s} \tag{5}$$

where T_m is the PV module temperature, T_a represents ambient temperature, W_s is the wind speed and U_0 and U_1 are respectively constant and convective heat transfer components, whose default values are 25 $\left(W/m^2\right)/C$ and 6.84 $\left(W/m^2\right)/\left[C \cdot (ms)\right]$ determined by Faiman for 7 silicon cell modules. The data implemented in this equation are measured during the annual experimental campaign every hours. From the determination of PV power variation according to the meteorological parameters, solar energy production could be computed. The battery charging state is regulated by a PWM (Pulse Width Modulation) controller, which acts as a switch connecting the solar array to the battery. This connection causes the PV voltage to drop close to the battery voltage. Consequently, not all the energy generated by the solar panel is transferred to the storage system, resulting in some energy loss. However, in the context of this preliminary analysis, an energy balance between PV module and the battery system was considered for simplicity. A more accurate model will be developed in future studies.

LED on-off schedule was determined considering GHI values, leading the lamp to turn on when solar radiation gets near to zero, whereas power supply switching from battery to grid was modelled as a function of battery state of charge (SOC), estimated with Coulomb counting method [24].

$$SOC = SOC_0 + \frac{\int Idt}{Q_{nom}} \tag{6}$$

where SOC_0 is the initial state of charge, considered as 100% in each scenario, Q_{nom} is the battery nominal capacity and I is the current, having negative sign if drawn from the stocking system. Voltage was determined through the capacity curve provided by the manufacturer. This curve was obtained by subjecting the battery to charging and discharging cycles at a C-rate of C/3 and a temperature of 20 °C (Fig.5).

For a 12 V $LiFePO_4$ battery, the typical cut-off voltage is 9 V. This voltage marks the point at which the battery ceases to supply power to the load. The voltage at which the power supply switches from the battery to the grid is defined as the over-discharge voltage (ODV). The manufacturer configured the over-discharge voltage (ODV) to 10 V, which fully discharges the battery (100% depth of discharge, DOD). According to the battery's datasheet, this setting offers a projected lifespan of 2,000 cycles, translating to approximately 5 years of operation. Grid consumption was estimated by assuming a 15% loss and a power factor of 0.98.

III. MEASUREMENT AND MODEL RESULTS

A. ELECTRICAL PARAMETERS RESULTS

The AC current drawn from the grid and the voltage measured during a typical week in March are presented in Fig.6(a). The corresponding global solar radiation measured by the weather station in the same period is reported in Fig.6(b). It is crucial to note that the AC current is predominantly sourced from the grid when the day prior exhibits cloud cover and the global solar radiation is insufficient to fully recharge the battery. These data, measured for about one year, were used for the validation of the model developed in Python language.

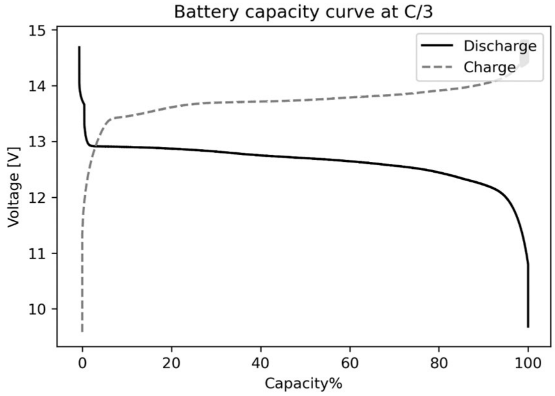


FIGURE 5. Battery capacity curve.

B. MODELS ANALYSIS

The algorithm was at first validated by running a simulation with locally measured meteorological data and comparing the results with real measured grid consumptions. Fig.7 and Fig.8 present the grid power (simulated and measured) and the power of the PV panel: results show a good correspondence between measured and simulated grid power both with tilt of 0° and 30°. The system tends to draw more energy from the grid during cloudy days, where PV power output is lower and less energy is taken in days with higher solar irradiance. In some cases, the real system starts to draw energy before the simulated one turns on, this difference is due to the fact that PV voltage has not been simulated in this preliminary analysis and on-off periods are regulated by POA. A tilt angle of 30°

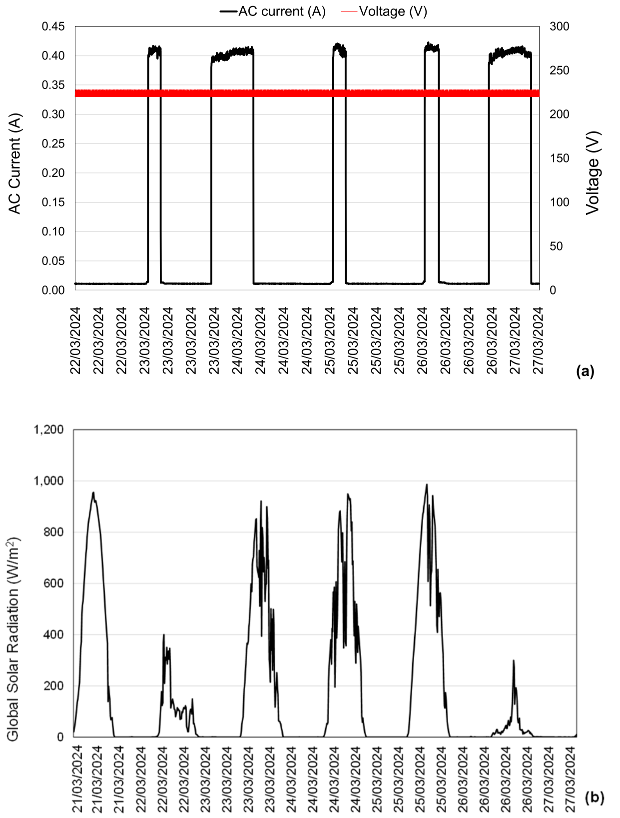


FIGURE 6. 100% power of the LED and 0°tilt angle: trend of the current supplied by the grid (the red line indicates the average voltage) (a); global solar radiation on horizontal plane (b).

results in a more optimal performance of the solar streetlamp, with a consistently lower electricity consumption from the grid, despite identical radiation conditions. The mean error in power prediction is 3.5% and 4.8%, respectively for 0° and 30° tilt angles.

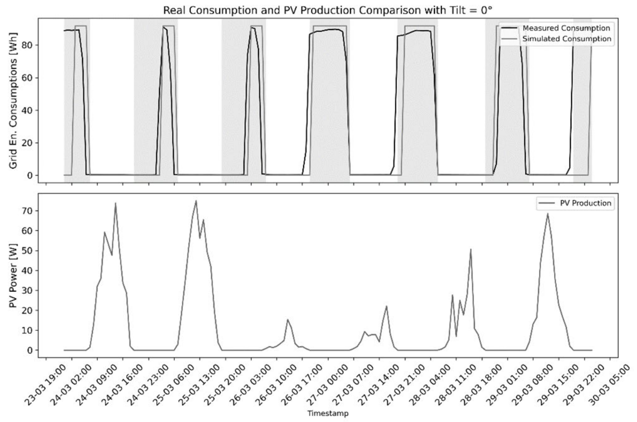


FIGURE 7. Comparison subplot showing real and simulated data alongside the PV power output for the same days with a fixed tilt angle of 0°. Highlighted areas indicate LED simulated activation periods. Local radiation data were used for these results.

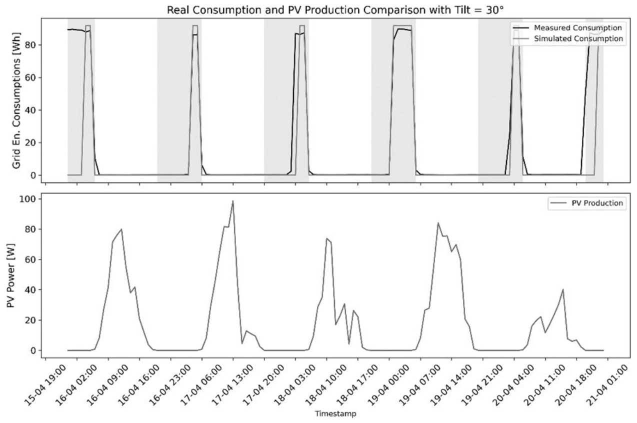


FIGURE 8. Comparison subplot showing real and simulated data alongside the PV power output for the same days with a fixed tilt angle of 30°. Highlighted areas indicate LED simulated activation periods. Local radiation data were used for these results.

By feeding the processed meteorological dataset to the algorithm, photovoltaic panel monthly energy production was estimated both with tilt angle at 0° and 30° by setting the azimuth angle at South in both cases (Fig.9). Implementing a tilted array results in an increase of approximately 12% in annual energy production. As depicted in Fig.9, having a tilted array particularly enhances the energy yield during the winter season, when the sun's position is lower in the sky and an inclined surface allows to better capture solar irradiance.

As shown in Fig.10, using a non-horizontal plane leads to lower energy consumptions given that, as previously said, the PV production is higher. In addition to that, tilt angle also influences the on-off schedule by affecting PV voltage and therefore energy consumptions. Fig.11 shows that the number of hours during which the system draws electricity from the grid is still high in winter (13 out of 15 hours of the night period in December and January) whereas the behavior is really better in summer (only 1 or 2 hours every night).

By summing the energy drawn from the grid by the lighting system over the course of a year in different schedules and angle settings, the annual electricity consumptions for a single streetlamp are illustrated in Fig.12. The differences between the tilt angles of 0° and 30° are about 10%, whereas the differences between a full LED power 100% schedule and a 100%-70% one are equal to 25%.

Energy savings were calculated by comparing the simulated annual consumption with a standard solution, considering the same number of operating hours, half of which with regulated power consumption. As shown in Fig.13, up to 45% of energy savings can be achieved with the analyzed solar street lighting system.

IV. LIGHTING PERFORMANCES

Artificial lighting simulation software was used to evaluate the lighting performance of the solar street lighting system. Two different scenarios were modeled in *Relux*, considering a typical local road configuration: an 8 m wide, two-lane,

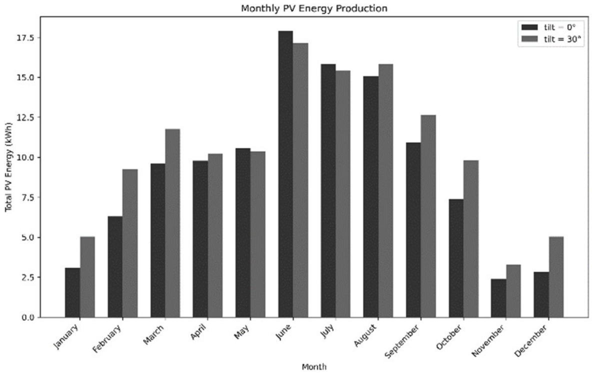


FIGURE 9. Monthly PV energy production with different tilt angles.

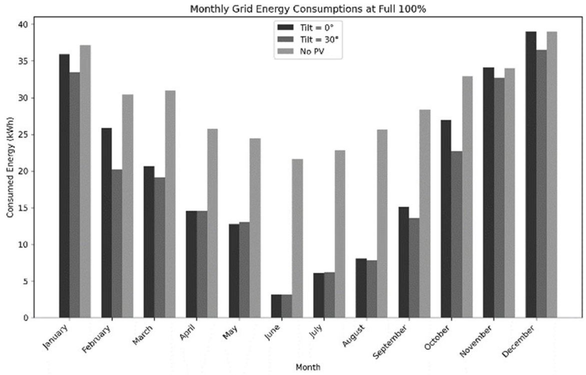


FIGURE 10. Monthly grid energy consumed by the system at two different tilt angles (0° and 30°) compared with the consumptions of the same system without PV.

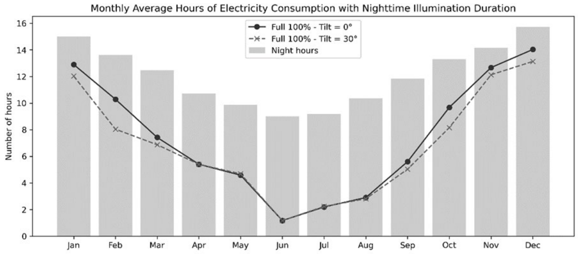


FIGURE 11. Monthly average amount of hours in which the system draws energy from the grid compared to the average number of night-time hours.

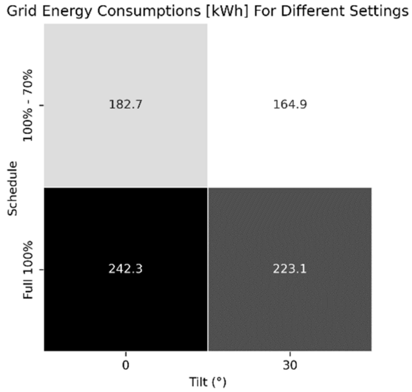


FIGURE 12. Yearly grid energy consumptions with different tilt angles and schedules.

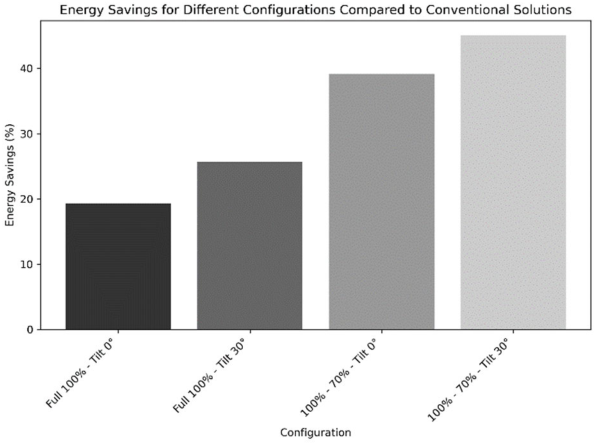


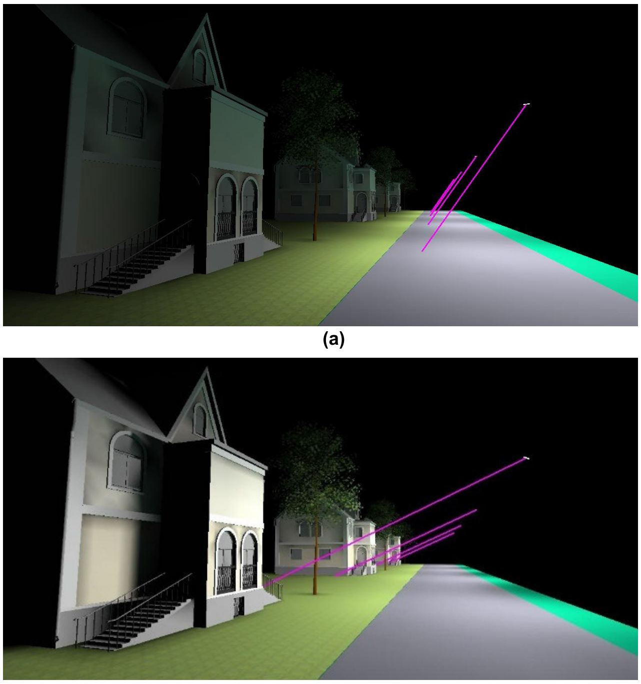
FIGURE 13. Energy savings compared to conventional street lighting solution with same power and post virtual midnight power regulation.

M3 class road, whose requirements are shown in Tab.2. M3 category was chosen because it is the most diffused in Italian territory. The first column represents the minimum luminance value that must be maintained on the road surface. The threshold increment (*TI*) is as the percentage increase in contrast required between an object and its background for the object to be seen equally well with a source of glare present. The luminance uniformity indexes (U_0 and U_L) are also included. Both luminance and illuminance values were calculated to assess the overall effectiveness of the lighting system and two distinct tilt angles were modelled: 0° and 30°. The optimal distance between luminaires was set at 23 m by the software and was considered as a fixed parameter to analyze the influence of the tilt angle. Photometric centers were positioned at a height of 8 m and overhang 0.5 m, a common setup for road lighting applications (Fig.14 and Fig.15).

TABLE 2. Street lighting requirements according to EN13201 [25].

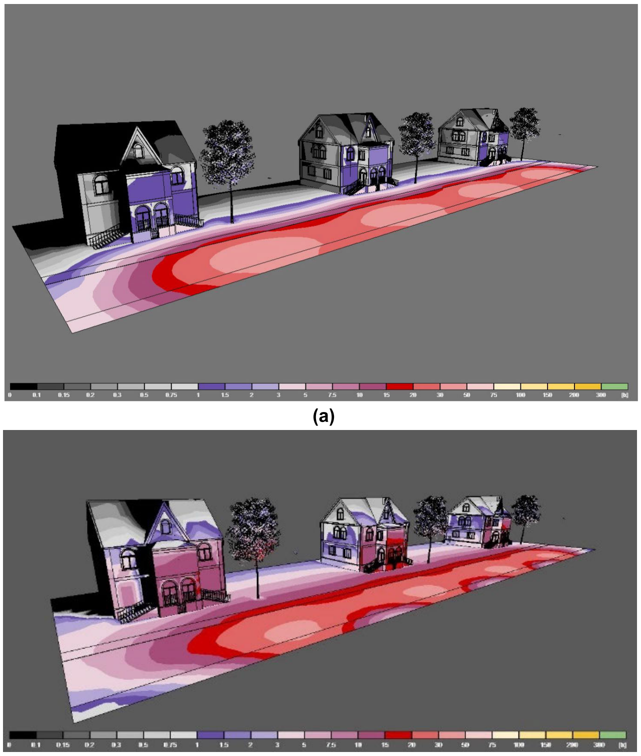
LC	$\overline{L}$ (cd/m^2)	TI (%)	U_0	U_L
M1	2.0	10	0.4	0.7
M2	1.5	10	0.4	0.7
M3	**1.0**	**15**	**0.4**	**0.6**
M4	**0.75**	**15**	**0.4**	**0.6**
M5	0.5	15	0.35	0.4
M6	0.35	20	0.35	0.4

As can be seen from Tab.3 and the corresponding renderings, the illuminance and luminance values are not greatly affected by the tilt angle, as the optics are quite wide and


(a)

(b)

FIGURE 14. Luminance rendering in an urban context with tilt 0° (a) and tilt 30° (b) at maximum power conditions.


(a)

(b)

FIGURE 15. Colors rendering of the illuminances (lx) in an urban context: (a) with tilt = 0° and 100% power of the lamp; (b) with tilt = 30° and 100% power of the lamp.

could be suitable for conflict areas. In the 30 - degree - tilt scenario, the 70% dimming factor leads to a luminance level which is insufficient for an M3 category, nevertheless, considering that power dimming only happens after virtual midnight when traffic is consistently reduced, the shift in the lighting category does not present an issue and it is allowed by standards. Fig.15(b) shows a disadvantage of using a 30° tilt angle. In fact, by directing the luminous flux beyond the intended road area, the surrounding areas are unnecessarily illuminated, with negative consequences for both the environment and residents [26].

The European standard EN 12464-2 [27] specifies regulations for obtrusive light, which are detailed in Tab.4. This standard considers four different environmental zones, labeled as E1 through E4. Zone E1 represents intrinsically dark areas, such as national parks or protected sites, while zone E4 represents highly bright district areas, such as towns or commercial areas. Vertical illuminance (E_v) must be measured on the windows area and *curfew* stands for the time after which stricter requirements for the control of obtrusive light should be applied, which usually starts at 23:00.

TABLE 3. Simulation results: Lighting performances for lane 1 at different tilt angles and LED's power.

LED Power	Tilt angle (°)	$\overline{E}$ (lx)	$\overline{L}$ (cd/m²)	TI (%)	U_0	U_L
100%	0°	29	**1.48**	**5**	**0.45**	**0.60**
100%	30°	24	**1.23**	**5**	**0.63**	**0.64**
70%	0°	20	**1.04**	**4**	**0.45**	**0.60**
70%	30°	19.5	**0.86**	**5**	**0.63**	**0.64**

TABLE 4. Maximum obstructive light permitted for exterior lighting installations according to EN 12464-2.

Zone	Pre-curfew E_v on properties (lx)	Post-curfew E_v on properties (lx)	Upward light ratio (R_{UL}) (%)	Luminance on Building facade (L_b) (cd·m^{-2})
E1	2	0	0	0
E2	5	1	5	5
E3	10	2	15	10
E4	25	5	25	25

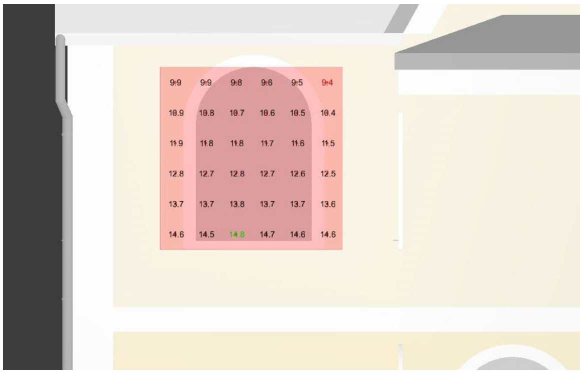
Upward light ratio was estimated to be 0% in both scenarios, because there is no amount of light going above the horizontal plane of the luminaire as the lighting flux is thoroughly directed downward. However, as denoted in European Green Public Procurement (EU GPP), the main cause of skyglow is the percentage of total light output above 90°, whereas obtrusive light is usually generated by the percentage of light going above 70° - 80°. As visible in Fig.15(b) and particularly in the map of Fig.16, by placing a calculation surface on the window of the building in the middle, the average illuminance is 12.2 lux, which is suitable for E4 categories, but not for darker areas. On the other hand, Fig.15(a) shows that the average illuminance on facades is lower than 1 lx, in compliance with EU GPP and standards. It is also important to specify that Tab. 4 shows the permitted maximum values considering all the lighting contributions in the evaluation areas.

V. CRITICAL ANALYSIS AND DISCUSSION

The developed analysis provided a preliminary study of the performance of grid-connected solar streetlights, addressing both their electrical performance measurements and the development of algorithms for optimal management.

The electrical and energy performance of this hybrid streetlamp can be further enhanced by means of a sizing optimization of the system taking into account the specific lighting conditions to be ensured, considering the solar radiation conditions of the site and trying to optimize the smart power derating curve showed in Fig.4.

A great advantage of these photovoltaic lighting systems is that they can be easily integrated in pre-existing infrastructures. Today's technological standards allow to produce optics that can guarantee an adequate level of luminance/illuminance with reduced power output. By comparing the case study photometric data with a similar optics having less nominal power and luminous flux, it can be observed that the light distribution is larger in the case (b) in Fig.17. This aspect allows for an increase in the distance between luminaires, resulting in cost and energy consumption reductions, suggesting that further improvements to LED optics are possible.



9.9	9.9	9.8	9.6	9.5	9.4
10.9	10.8	10.7	10.6	10.5	10.4
11.9	11.8	11.8	11.7	11.6	11.5
12.8	12.7	12.8	12.7	12.6	12.5
13.7	13.7	13.8	13.7	13.7	13.6
14.6	14.5	14.8	14.7	14.6	14.6

FIGURE 16. Scenario with tilt angle of 30° and 100% power: illuminance calculation grid on the left window of the building in the middle.

For the same road type considered previously, *Relux* program calculated the optimal distance to be 30 m, meaning that a consistent reduction in the number of street lightings could be installed reducing capital costs. This implies that, considering a street 1 km length only 33 streetlamps with the new optics features are necessary (instead of a total number of 44 streetlamps and 23 m of distance between each pole as previously fixed in the actual conditions). Therefore, suitable values of luminance could be obtained by using better optics and lower nominal power, an aspect that could extend battery duration time during the night and, therefore, decrease energy consumptions.

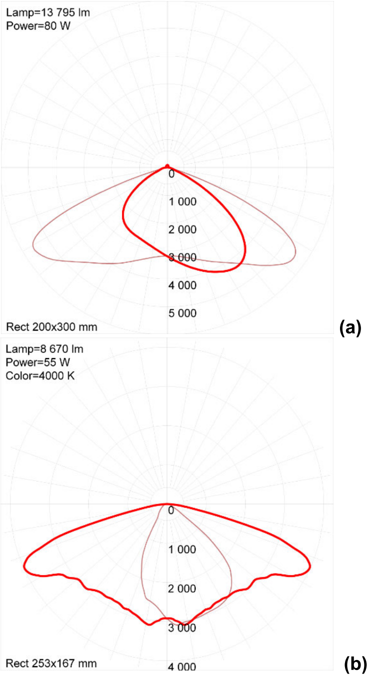


FIGURE 17. (a) Case study's photometric curve; (b) Photometric curve of a less powerful lamp but with comparable application results.

To conduct an economic analysis, the replacement of the already existing old luminaires was supposed by considering the optics displayed in Fig.17(b), which output the results in Tab. 5. Although the configuration with a 30° tilted plane could result in a consistent energy saving, in practical applications luminaires are typically not tilted more than 10° to avoid light pollution and glare effects to meet the obtrusive light standards.

Taking these considerations into account, a tilt angle of 10° was chosen and the consumption associated with the new optics was taken into account, based on the total power of the lamp (55 W) and the efficiency (157 lm/W). Furthermore, a better usage of the battery was also implemented in order to further reduce maintenance costs: the depth of discharge (DOD) of the battery has been set at 80% (SOC works between 20 and 90%), which could extend the lifespan of the battery but increase the consumption of the network, as shown by the trend of electrical power drawn from the grid in Fig.18.

The developed algorithm is capable of calculating the annual number of cycles of the battery for a typical year. A yearly simulation was conducted, taking into account the solar conditions of Perugia (weather file with the hourly

TABLE 5. Lighting performances for lane 1 at different tilt angles and LED's power for the second optic conditions (P = 55W).

LED Power	Tilt angle (°)	$\bar{L}$ (cd/m²)	TI (%)	U_0	U_L
100%	0°	**1.45**	**11**	**0.41**	**0.84**
100%	30°	**1.04**	**11**	**0.60**	**0.70**
70%	0°	**1.02**	**11**	**0.41**	**0.84**
70%	30°	**0.76**	**10**	**0.66**	**0.74**

data of global solar radiation on horizontal and tilted panes and of the outdoor mean air temperatures [28]) and the new assumptions previously discussed. The results are presented in Table 6, which shows that the annual electricity consumption has increased by approximately 37-45%. Given that the annual electricity consumption is assumed to be 236 kWh for a standard grid-connected streetlamp with no renewables applied, the savings range from 40% to 48% with a depth of discharge set at 80%. When the maximum DOD is fixed at 80%, the battery cycles number increases from 2000 to 3800, and the corresponding lifetime reaches 10.5 years, in comparison to the 5.5 years of the standard operating profile [29], [30].

On the basis of these discussion, a final economic scenario was reported considering the replacement of old LED luminaires with the photovoltaic ones. An estimated investment cost of about 500 €per luminaire, inclusive of installation costs, and an electricity cost of 0.23 €/kWh were supposed (mean value observed in Italy in 2023 [31]). The cash flow is represented in Fig.19, considering the two different maximum DOD sets for the battery (100% or 80%) and a mean PV tilt angle of 10°; The rate of discount was fixed at 3% and the substitution of the lithium-based batteries is assumed every 5 years when the maximum DOD is 100%, and every 10 years when the maximum DOD is fixed at 80%. These values were derived from the number of cycles completed by the batteries and calculated by the algorithm in both cases.

Furthermore, the substitution of the lamps was calculated to occur after 50,000 hours, which is the expected lifetime for this model of lamp. The algorithm is capable of calculating the total number of cycles undergone by the street lamp on an annual basis. Both the Payback Time (PbT) and the Net-Present Value (NPV) of the investment are calculated: in both the cases the pay-back period of the investment is very high but when the maximum DOD is 80% the value is lower (18 years) even if the yearly electricity savings are lower. For a maximum DOD of 100% the period is not acceptable and inconsistent with the lifespan of the lamppost (batteries replaced 5 times in 25 years).

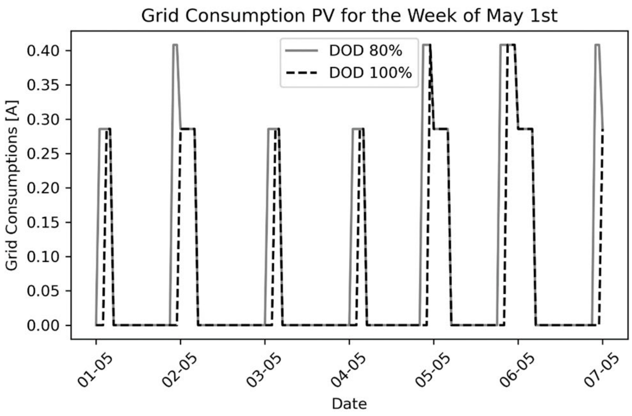


FIGURE 18. Current drawn from the grid with different battery DOD% settings with 100%-70% operative schedule and tilt = 10°.

TABLE 6. Yearly grid electricity consumptions in different scenarios with the new photometric curve and features of the lamp (P = 55 W).

Maximum DOD (%)	Tilt angle (°)	Electricity from the grid (kWh)
100%	0°	101.9
	10°	94.2
	30°	84.0
80%	0°	140.4
	10°	132.5
	30°	122.2

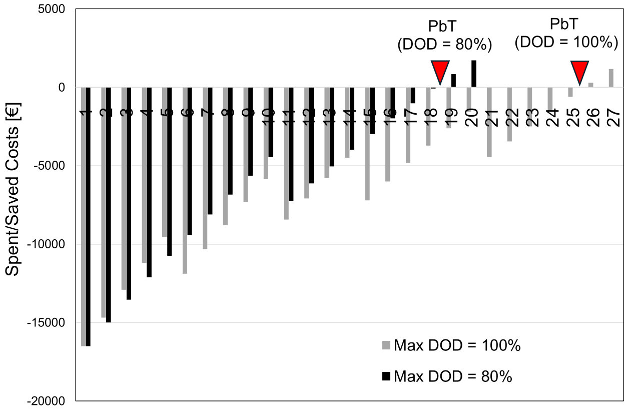


FIGURE 19. Cash flow of the investment for the solar streetlamp with south orientation, 10° tilt angle, 100-70% program of operation: current costs.

This highlights the importance of further optimizing the system to enhance its economic viability, also in terms of operating configuration.

The cash flow in Fig.20 shows that if the costs of lamp replacement and storage were reduced to the actual price (half of the original value for the solar street lamp, around

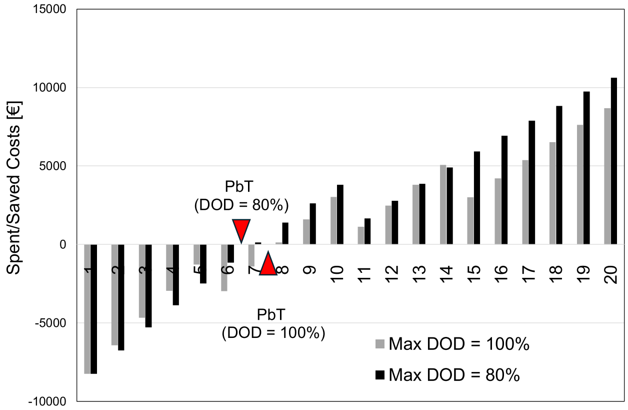


FIGURE 20. **Cash flow of the investment for the solar streetlamp with south orientation, 10° tilt angle, 100-70% program of operation: future scenario with reduced costs.**

€250, and around €180/kWh instead of €200/kWh for the batteries with a 10% reduction), the PbT would be 6 and 7 years respectively for DOD_{max} equal to 80% and 100%. This is in line with the lifetime of PV-based street lights, which is assumed to be 20 years. The Net-Present Values are about 8,700 €(first scenario with $DOD_{max} = 100\%$) and 10,700 €(second scenario with DOD max = 80%).

VI. CONCLUSION

The analysis underscores the promising potential of hybrid solar street lighting systems for sustainable urban development. By integrating renewable energy sources with advanced management algorithms, these systems offer resilience, reliability, and significant energy savings.

A solar-powered streetlamp with an innovative design was installed in an Italian city and the electrical parameters were monitored for approximately one year, in conjunction with the environmental conditions of the site. The data were used to develop an algorithm that is capable of simulating the behavior of the PV-powered streetlamp in different weather conditions and for different schedules. Additionally, lighting simulations were conducted in order to evaluate the illuminance and luminance values that are ensured on the road, as well as the potential glare effects that may be caused by the orientation of the lamps. An optimal tilt of the PV panel was defined and new optics and photometric curve were chosen in the final analysis in order to reduce the number of street lamps necessary in a certain road section. The algorithm was used to simulate the optimized configuration, with particular attention paid to the maximum DOD set for the lithium-based battery. It was found that if the state of charge (SOC) of the battery is maintained at a level above 20%, the lifetime of the storage system is increased, and the need for battery replacement is postponed. In fact, It can be confirmed that the number of cycles for the batteries increases in line with a decrease in depth of discharge. Both a maximum DOD of 100% and 80% were taken into account in the algorithm management profile, and the annual number of cycles was counted in order to ascertain the number of years after which it is necessary to substitute the batteries. In conclusion, an economic analysis was carried out to determine the payback time of the investment and the net present value, taking into account the costs of the PV-based luminaires and the batteries.

Despite the initial investment costs and challenges related to system optimization, the study demonstrates the benefits of adopting hybrid solar lighting in urban environments. Further researches and a more holistic approach are essential to fully realize the economic and environmental advantages of these systems, taking into account both sustainability aspects and energy performance, and minimizing the impact on the grid with careful planning. This will pave the way for a more sustainable and energy-efficient urban future. A reduction in the costs associated with both the PV panels and the $LiFePO_4$ storage will result in an acceptable NPV and PBT for the investment, thereby making this model for the integration of renewables in public lighting systems replicable in other contexts, such as microgrids, smart grids, and renewable energy communities.

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