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RESEARCH ARTICLE

Implementation of a New Solar-Powered Street Lighting System: Optimization and Technical-Economic Analysis Using Artificial Intelligence

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ABSTRACT Public lighting system represents a key role in the energy transition process, considering the high electricity consumptions related to this sector. The integration of renewables could be suitable for this application and many solutions of solar-based lamps for street lighting are spreading. In this research work, a specific application of a PV-integrated lighting system was installed in the center of Italy along a footpath and monitored for several months, both in terms of electricity parameters and lighting behavior. It is equipped with monocrystalline photovoltaic cells, a lithium-based battery, and a LED lamp. The measured data allow the development of an optimization algorithm in Python program for the correct management of the solar streetlamp and the forecasting of electricity consumptions for different boundary conditions (e.g. Italian geographical position). The energy taken from grid in a year is very low with respect to a traditional lamp not powered by renewables: only 43-46% in central-northern regions and 35% in south region. Data are also used to study the possible substitution of all the traditional lamppost of the walkway with the novel proposed system. A technical-economic analysis is carried out to analyze the effectiveness of this solution not only in terms of electricity consumptions reduction, but also costs savings. The suitability of the investment and the payback time depend on Italian national price of electricity and initial cost of the solar lamp. The results can be applied to similar case studies in Italy to save electricity consumptions and reduce CO_2 emissions.

INDEX TERMS Artificial intelligence, electricity consumptions, LED, optimization algorithm, photovoltaic (PV), storage, streetlamp, technical-economic analysis.

I. INTRODUCTION

Street lighting is a crucial system for ensuring safety, aesthetics, economic rewards, and community well-being. First and foremost, street illumination is essential for public safety. Well-lit streets create an environment where pedestrians, cyclists, and drivers can move with confidence, reducing the risk of accidents and enhancing overall road safety. Adequate illumination values not only help people to identify potential hazards, but also acts as a deterrent to criminal activities, encouraging a sense of security among residents and visitors.

Properly constructed and strategically positioned lights transform the night cityscape into a visually appealing sight. The interaction of light and shadows not only enhances the architectural beauty of surroundings but also contributes to the creation of vibrant and livable urban spaces. A city with a

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well-designed public lighting system contributes to maintain a sense of warmth, making public areas more inviting and fostering a sense of community [1].

Beyond safety and aesthetics, street lighting provides economic benefits for communities. Well-lit streets encourage longer business hours, which promotes nightlife activities and boosts the local economy. Retail establishments, restaurants, and entertainment venues all benefit from the increased foot traffic facilitated by well-lit thoroughfares. In this scenario, street luminaries become an integral part of urban planning, supporting economic growth and community development.

Smart cities are ideal venues for sustainability measures aimed at reducing energy consumptions and the green-house-gasses emissions GHGs. Particularly, street lighting system is responsible for nearly 50 billion kWh of electricity every year and it is important to take strategic actions on this sector. In the goal of sustainable urban development, the adoption of solar-powered street lighting systems stands out as a critical step towards harnessing renewable energy sources and mitigating environmental effect [2]. This innovative approach not only addresses the pressing need to reduce carbon emissions, but also offers substantial cost savings, marking a significant rise towards more sustainable and economically efficient future conditions.

One of the primary advantages of solar-powered street lighting lies in its reliance on renewable energy from the sun. By using photovoltaic (PV) panels to convert sunlight energy into electricity, these systems can operate off-grid, (stand-alone application with batteries able to reduce the dependence on traditional power sources), or grid-connected (with a consistent economic saving). This not only promotes environmental sustainability but also enhances the resilience of urban infrastructure by decreasing vulnerability to power outages and disruptions. Furthermore, the environmental benefits allow a substantial reduction in CO_2 emissions [2], [3]. This transition to cleaner energy sources aids in creating more eco-friendly cities, fostering a healthier and more sustainable living environment for communities.

In addition to the environmental advantages, the economic impact of PV-based street luminaries cannot be neglected [4]. The initial investment in solar infrastructure is offset by long-term cost savings, as these systems generate electricity without ongoing fuel expenses. Municipalities can benefit from reduced energy bills, which can free up funds for other essential urban development projects [5], [6]. Hence, the importance of streetlamps transcends mere visibility during night. As cities continue to evolve, it is important to highlight the vital role that well-designed and efficiently implemented street lighting plays in shaping the character and functionality of urban conditions. All these aspects induced many researchers and scholars to explore and investigate new solutions for the application of renewables [7], [8], [9] and the use of new techniques able to correctly manage the lighting systems [10], [11], [12], [13].

The aim of the present research study is the analysis of energy, economic, and environmental performances of a PV-integrated streetlamp. It is installed along a pedestrian path in Italy center (Perugia) and the electric behavior was monitored for about 1 year. Data are collected and used for the development of a complex artificial intelligence tool for the forecasting of the performance in different locations and setting of the lamp. Not only the energy and electricity performances but also the economic and environmental benefits achievable through the solar streetlamp are examined.

The article is structured as follow: after the introduction, section II concerns the description of the novel solar-based lamppost and the context of the installation. Moreover, the methodologies of the on-site measurements (electric and lighting parameters) and the proposed mathematical algorithm are shown. Section III describes the results of the measurements (section III-A) and of the simulation analysis, by also including a cost analysis applied to the case study (section III-B and III-C). A conclusion paragraph is finally reported with the most significant critical observations.

II. MATERIALS AND METHODS

A. THE CASE STUDY DESCRIPTION

PV lighting applications are generally suitable where low light levels and limited electric power are required or where the access to a grid is problematic. The specific solution is installed in the center of Italy in a green pedestrian area where the mean illuminance to be maintained are not so high. The pedestrian road is assimilated to a P2 lighting category in compliance with CEN TR 13201-1 and EN 13201-2 [14], [15], (not only green areas, footways, and cycle-ways but also parked vehicles are present in limited zones) with a mean illuminance to be assured equal to 10 lx and a minimum one equal to 2 lx. The section of the pedestrian road considered as case study presents n.9 high pressure sodium luminaries with a total peak power equal to 121 W, a duration of only 24000 hours, the efficiency is 120 lm/W and the high of installation is 8 m. These lighting systems are programmed to be turned-on during the whole night period at the maximum peak power.

The experimental PV-lighting system is installed in this green area along the path between two standard luminaries. Considering its technical features, it is programmed in compliance with the other lamps, but the power is fixed at 24 W (50% of the maximum value) until midnight because it is enough for maintaining the mean illuminance values on the reference surface. In the period from 0 a.m. to 4 a.m. the intensity is fixed at 25% (12 W) and it is increased again for the last hours in the morning. As well as the other lamps, it is programmed to work during night in compliance with seasonal sunlight conditions (about 12 hours in winter, 10-11 hours in Autumn and in Spring, 8-9 hours in summer). The lamp switches on/off based on astronomical clock and a dusk sensor that allows to set the automatic right time to light up.

The electric and the lighting parameters were monitored in the period February 2023 – January 2024. In Figure 1 photographs of the PV-integrated lighting solution installed in the green area are shown; Figure 2 represents the map (Figure 2a) and the 3D view (Figure 2b) of the placing of the new system in the cycle/pedestrian path. As observed from the photos and the map the position was chosen to allow minimal shading conditions and maximum solar irradiance.

FIGURE 1. **Photos of the solar based lamp installed on-site.**

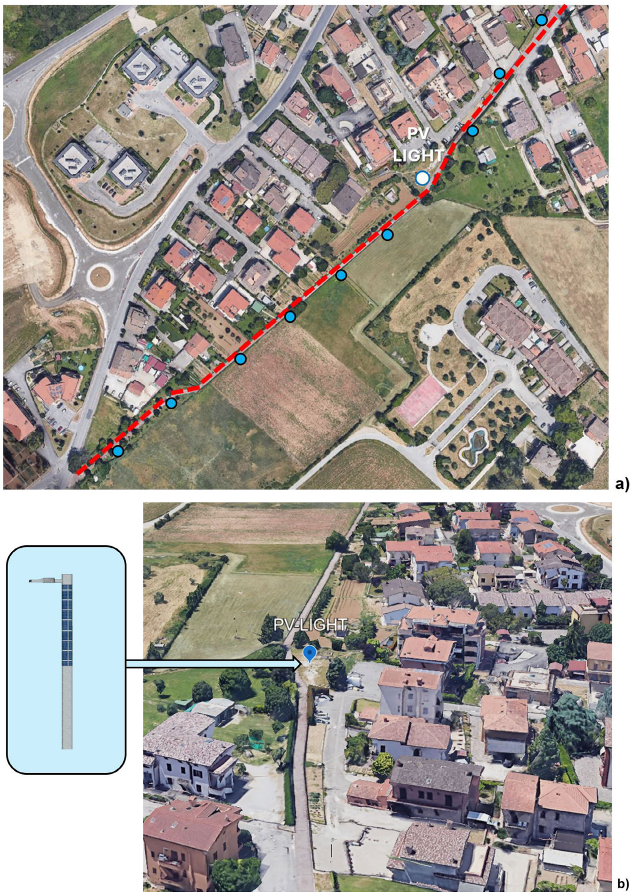


FIGURE 2. **a) Mapping of the green area and positioning of the traditional lampposts (light blue circles) and the PV-streetlamp (white circle); b) 3D view and position of the PV-lighting system along the path.**

B. THE SOLAR LIGHTING SYSTEM ARCHITECTURE

PV lighting system components include the PV system, batteries, electronic components (such as battery charge controller, inverter or ballast/driver), the lamp, the lighting appliance, and the pole. The investigated system presents a LED lamp with a total maximum power equal to 48 W (load voltage 44 V) but it can be dimmed considering the illuminances to be maintained on the roads. The LED lamp chosen for this application has a high efficiency equal to 120 lm/W, a color rendering index higher than 90%, and a color temperature of 4000 K; the intensity distribution curve of the lamp is symmetric, and the lifetime is more than 100000 h. The operational program of the unit is managed by a specific developed software and the power of the lamp is dimmed with a minimum time step of 15 minutes. In this case a time step of 1 hour was chosen for the scheduling. The aluminum support pole has a total diameter of 0.20 m and it is 4 m high. The cylindrical solar surface is constituted of flexible high efficiency monocrystalline PV cells with a total area of 630 × 1800 mm and a peak power of 200 W. The single solar cell has a power of about 2 W. In the case a mismatch condition occurs in short-circuit current between a series of connected cells, a bypass diode is connected in parallel to a solar cell to conduct the current allowing the electric flow in the external circuit and avoiding excessive losses.

A Lithium-based battery ($LiFePO_4$, charging voltage of 14.6 V, operating voltage of 12.8 V, and a capacity equal to 36Ah) located inside the pole with a life-time of 3 years (about 2000 cycles) is installed. The charging efficiency of the battery depends on the weather conditions observed in that day. During the night, energy from battery is used to supply the lighting load but when the battery state of charge (SoC) falls below 20% the electricity is taken from the grid for maintaining minimum power conditions of the lamp.

A solar charge controller, a terminal block circuit, and a battery management system (BMS) are also installed. The solar charge controller is an electronic device able to check the excess voltage from the solar panel that is the reason why the battery duration is reduced. A Maximum Power Point Tracking (MPPT) algorithm is used for maximizing the energy transferred to the battery when the solar radiation is quite low; in sunny days the battery charging current is fixed at the maximum permitted value.

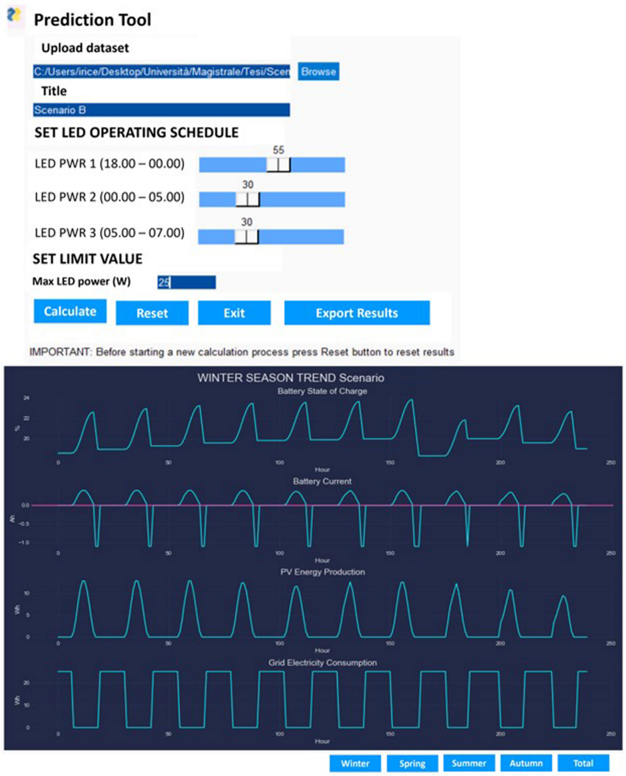
During charging, battery-current value depends on the PV power production and consequently on the global solar radiation on the PV surfaces; the battery voltage level depends on the charging current and on the SoC of the battery itself.

C. ELECTRIC AND ENVIRONMENTAL MEASUREMENTS

During the reference period, sensors installed inside the pole recorded the electric parameters. Moreover, they are reprocessed by the program *srne.lampmonitor* [16]. In particular, the battery voltage and current (V_b, I_b), the energy entering and outgoing the battery (E_b), LED lighting module voltage (V_{led}), and current waveforms when the lighting system works (I_{led}), the power of the lamp (P_{led}), the load voltage and current of the PV system immediately following the MPPT charge regulation (V_{PV}, I_{PV}) and the energy produced by the PV plant (E_{PV}) are acquired by the sensors. The state of charge (SoC) of the battery at a given time is estimated by the program starting from the SoC at the previous time, the charging or discharging current at this time and the nominal battery capacity (Coulomb counting method).

The weather data are measured by a monitoring station located near the installation site: the global solar radiation on horizontal surface (accuracy 1 W/m^2) and the mean outdoor air temperature (accuracy 0.1 °C). Data are used to analyze the accordance between the measured solar radiation and the PV cells production and for the training of an algorithm that will be discussed in the following section.

For defining the operating schedule of the lamp, an experimental campaign was carried out during night for evaluating the illuminances for different percentage reductions of the power of the lamp. A HT309 luxmeter was used for illuminance tests (measurement range 0 – 400000 lx). The measurements were carried out according to a grid of points that allowed a spatial analysis: 60 positions were chosen uniformly distributed in the influence area of the pole.



Prediction Tool

Upload dataset

C:/Users/irice/Desktop/Università/Magistrale/Tesi/Scen

Title

Scenario B

SET LED OPERATING SCHEDULE

LED PWR 1 (18.00 – 00.00) 55

LED PWR 2 (00.00 – 05.00) 30

LED PWR 3 (05.00 – 07.00) 30

SET LIMIT VALUE

Max LED power (W) 25

IMPORTANT: Before starting a new calculation process press Reset button to reset results

FIGURE 3. User interface of the developed forecasting program.

D. ALGORITHM DEVELOPMENT

The algorithm for the simulation of the electrical and energy performance of the PV-integrated lamp is developed in Python programming language [17], [18]. The tool can forecast the behavior of the solar streetlamp during the year and for different boundary conditions [18].

The input data are the current and the voltage trends outgoing the PV system (I_{PV}, V_{PV}) that can also be estimated from the global solar radiation of the site. For this purpose, the measurements carried out during the reference period can be used to train an artificial neural network (ANN 1) developed in a previous research work [19]. To evaluate the voltage and current output of the PV system, a second feedforward ANN (ANN 2) is trained. The MPPT charge regulator setting was taken into account with respect to the values directly output by the PV cells (80% of the data was used for the training and 20% for testing). A final configuration was obtained, resulting in very low computational costs (correlation coefficients R were equal to 0.92 and 0.96 for the voltage and the current, respectively).

An initial interface is developed to allow the user to fix the input parameters and the schedule of the lamp in the night: up to three periods can be set with different powers of the lamp based on the required street lighting category and the expected presence of pedestrians and cyclists (Figure 3).

The boundary conditions established in the tool are the limits of the battery voltage for maintain the SoC of the battery higher than 10% and the power of the lamp that should not drop below a minimum value able to maintain the illuminances (24 W in the specific case). The output parameters of the tool are the battery charging and discharging trends in terms of voltage and current (V_b, I_b, and the corresponding SoC), the voltage and the current supplied to the lamp (V_{led}, I_{led}), the power (P_{led}) and the hourly electrical consumptions of the lamp; they can be observed graphically but they can also be exported as numerical data. When the minimum LED power could not be maintained because of the low SoC of the battery ($\leq$20%), the proposed algorithm finds the correspondent hourly lacking energy that should be taken from the grid. These values can be used for daily, weekly, monthly, seasonal, or annual analysis and they are the values that can be also implemented for the economic analysis that will be described in the subsequent section. The flow chart of the algorithm is represented in Figure 4.

E. ECONOMIC ANALYSIS

To complete the algorithm application and the technical and energy investigations, an additional tool for economic analysis is also proposed. This tool will study the effectiveness and the convenience of installing the new solar streetlamp in a selected case study on an annual basis and within useful time horizon. In particular, the yearly electricity taken from the grid of a single solar-based lamp can be calculated as shown in (1) whereas the annual energy consumption of the standard

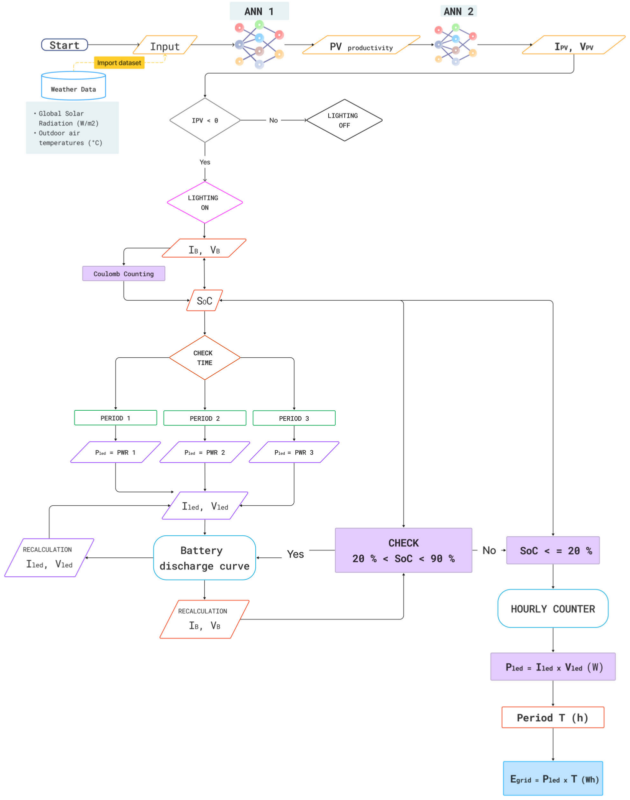


FIGURE 4. Flow chart of the developed algorithm.

solution is obtained from (2):

$$E_{grid}^{solar} = \sum\nolimits_{month} N^{month} \cdot \left(T_1^{month} \cdot PWR1 + T_2^{month} \cdot PWR2 + T_3^{month} \cdot PWR3\right) [\text{Wh/year}] \tag{1}$$

$$E_{grid}^{standard} = \sum\nolimits_{month} N^{month} \cdot \left(T_1^{month} + T_2^{month} + T_3^{month}\right) \cdot \Phi/\eta [\text{Wh/year}] \tag{2}$$

where:

$$\eta = \frac{\Phi}{PWR}\left[\frac{\text{lm}}{\text{W}}\right] \tag{3}$$

N represents the number of days each month; T_1, T_2, and T_3 are the hours of the night in which electricity is taken from grid in every month *PWR1*, *PWR2*, and *PWR3* are the setting power of the PV-integrated lamp during the on-period. For the standard solution the powers of the lamp for each of the three periods are calculated by considering the efficiency of the lamp η (calculated in (3)) and the lighting flux (Φ) to be maintained to reach the same illuminances on the path. Moreover, a cost of electricity taken from the grid C_{el} equal to 0.12 € /kWh is considered [20]. Given these assumptions, in a typical year the annual cost saving (C_s) is calculated as following:

$$C_s = \frac{(E_{grid}^{standard} - E_{grid}^{solar}) \cdot C_{el}}{1000} [€/\text{year}] \tag{4}$$

For the costs analysis it is necessary to know the initial investment (I_0^{solar} and $I_0^{standard}$) and the maintenance costs of the new system with respect to a standard streetlight. The model discussed in this research work has a cost of about 3500 € per unit (about 2.3 times higher than the standard lamppost, $I_0^{standard}$). In the annual cost calculation, the maintenance costs of the several components of the solar-based lamp (such as PV cells, LED lamp, battery, MPPT charge controller) should be counted; the replacement of LED drivers is also considered (only 1% every year for 15 years because of the high efficiency of LEDs). The yearly electricity costs for the operation and maintenance are named C_{maint}.

The manufacturer of LED lamps guaranteesa lifetime period of 100000 hours. Therefore, for a maximum on-period of 4200 hours per year, the forecast period of 15 years is suitable, and it is also consistent with the lifetime of PV systems. The lifetime of high-pressure sodium lamps is approximately 24000 hours, so they should be replaced every 6-7 years. An annual discount rate r is considered (equal to 5%), the substitution of the lithium-based battery is assumed every 4 years (with a cost of 150 €, 3 times during the lifetime of the lamp). Considering these contributes, a cash flow is obtained in the selected interval of time. The total cost saving at the end of the useful life is the Net Present Value (*NPV*) of the investment: *NPV* is determined by considering the costs (negative cash flows) and benefits (positive cash flows) for the period of the investment and it is calculated as in (5):

$$NPV = \sum\nolimits_{k=1}^{15} \frac{C_{s,k}}{(1+r)^k} - \sum\nolimits_{k=1}^{15} \frac{C_{maint,k}}{(1+r)^k} - \left(I_0^{solar} - I_0^{standard}\right) [€] \tag{5}$$

where k is the year (from 1 to 15). A Payback Time (PbT) is therefore obtained (the period – number of year - required to supply the initial outlay in terms of profits or savings).

III. RESULTS

In this section the on-site performance of the solar-based streetlamp is analyzed thanks to the measurements carried out in the reference period. Furthermore, the mathematical results obtained from the developed program are discussed.

A. IN SITU PERFORMANCE OF THE PV-LIGHTING SYSTEM

As previously specified, the on-off profile of the light is established by examining the illuminance behavior of the lamp and maintaining the minimum illuminance on the roads. The map of illuminances obtained when the lamp has the minimum power is shown in Figure 5.

The illuminances are higher than 2 lx (4.6 lx) and the mean values in the reference area are higher than 10 lx (17.3 lx). The schedule profile previously described in section II-B is also chosen considering the probability distribution of the people passage. Weather data were used for analyzing the accordance between the measured solar radiation and the PV cells production: a good agreement was observed in several months, as shown in Figure 6 for two selected days in June

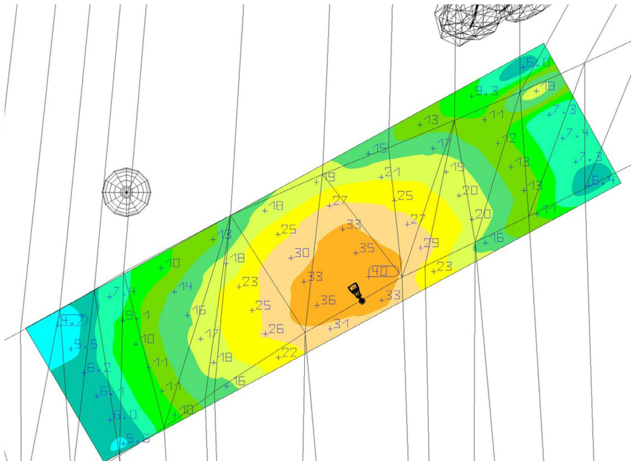


FIGURE 5. **Illuminance measurements maps for the minimum peak power of the lamppost.**

and October. The divergences and not perfect correspondence of the peak values are due to the configuration of PV cells that are disposed on a vertical surface around the pole and they are never simultaneously irradiated (maximum production of about 45 Wh). Electric measurements are examined for three days in summer (August 7-9, 2023 in Figure 7) and in winter (December 16-18, 2023 in Figure 8). In particular, the voltage and current outgoing the PV surface (V_{PV}, I_{PV}), the LED lighting module voltage (V_{led}) and current (I_{led}) trends when the lighting system continuous works, the SoC of the battery and the charging/discharging current are monitored and analyzed for the selected periods. In Figure 9 you can observed that the three selected days both in summer and in winter are quite sunny but the solar radiation on horizontal plane reaches 1000 – 1200 W/m^2 in summer and only 450 W/m^2 in winter. It can be observed that in summer the PV voltage is maximum and higher than 20 V when the current outgoing the PV cells is minimum due to the complete recharge of the battery: in fact, I_{PV} is more than 2 A when the battery is being recharged and it drops to about 0.3 A when the SoC is about 100%.

In summer the SoC of the battery varies between 40% and 100% and the system maintains the LED on without supplying electricity from the grid. In Figure 7 (b) the LED on/off profile is shown: the on-period is between 8:00 p.m. and 5:00 a.m. and the LED power is maintained equal to 24 W until midnight and between 4 a.m. – 5 a.m., 12 W between 0 a.m. and 4 a.m. In winter the LED working profile is the same but the on period of the lamp is higher than summer (about 13 hours) due to the lower number of sunny hours. The PV production is not enough to cover the entire on-period of the lighting system as shown in Figure 8 (b) and the lack of electricity is taken from the grid (grey dotted line in Figure 8 (b)). As shown in Figure 8 (c), a part of the electricity is taken from the grid when the SoC is lower than 20% and it is totally provided by the grid when the SoC drops to about 10%. Finally, the yearly analysis of the measurements is examined in terms of energy in Figure 10 (from February 2023 to January 2024).

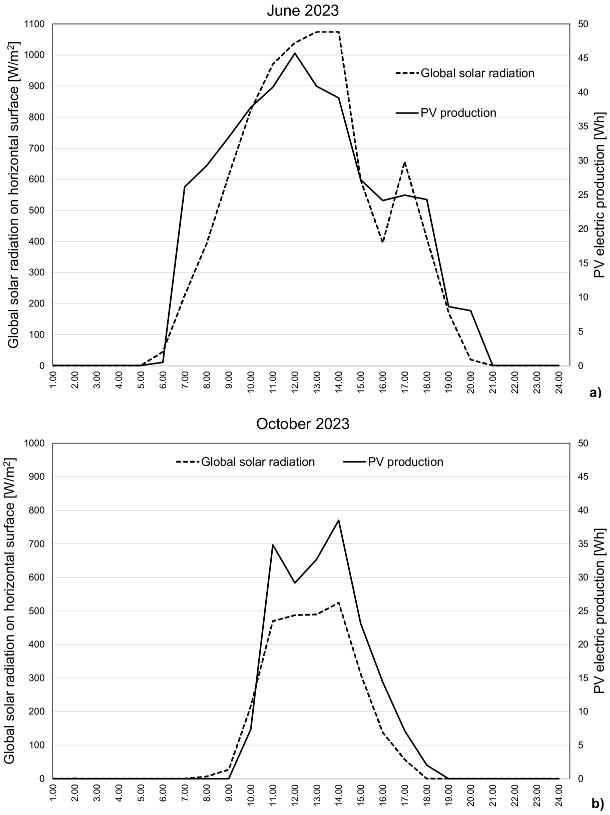


FIGURE 6. **Comparison between solar radiation and PV productivity trends in two selected days: a) June 2023; b) October 2023.**

The monthly PV energy production is in line with the average daily solar radiation: the total LED consumptions are compared with the monthly energy supplied from the grid to maintain the lighting profile and the corresponding number of hours in which the battery is not self-sufficient (minimum in summer, about 35-45 hours every month, maximum in winter, up to 150 hours in January). It is possible to conclude that the annual energy consumptions of the light are 72 kWh, about 41 kWh are covered by the PV production (57% of the total amount), about 43% is taken from the grid (a great part in winter months).

B. ENERGY SIMULATION RESULTS

Results of the algorithm are analyzed in this section considering the energy aspects of the plant applied to a case study. The algorithm previously described is developed thanks to the electric data collected in the year. After tuning, the performance of the PV-based lighting system is studied in three different Italian locations considering as input the weather parameters of Perugia (center of Italy), Bolzano (Italy north), and Catania (Italy south) (BZ, PG, and CT, respectively, located as shown in Figure 11).

The PV production is simulated taken into account the global solar radiation profiles of each city and the LED lighting on-off schedule is consequently modified on the basis

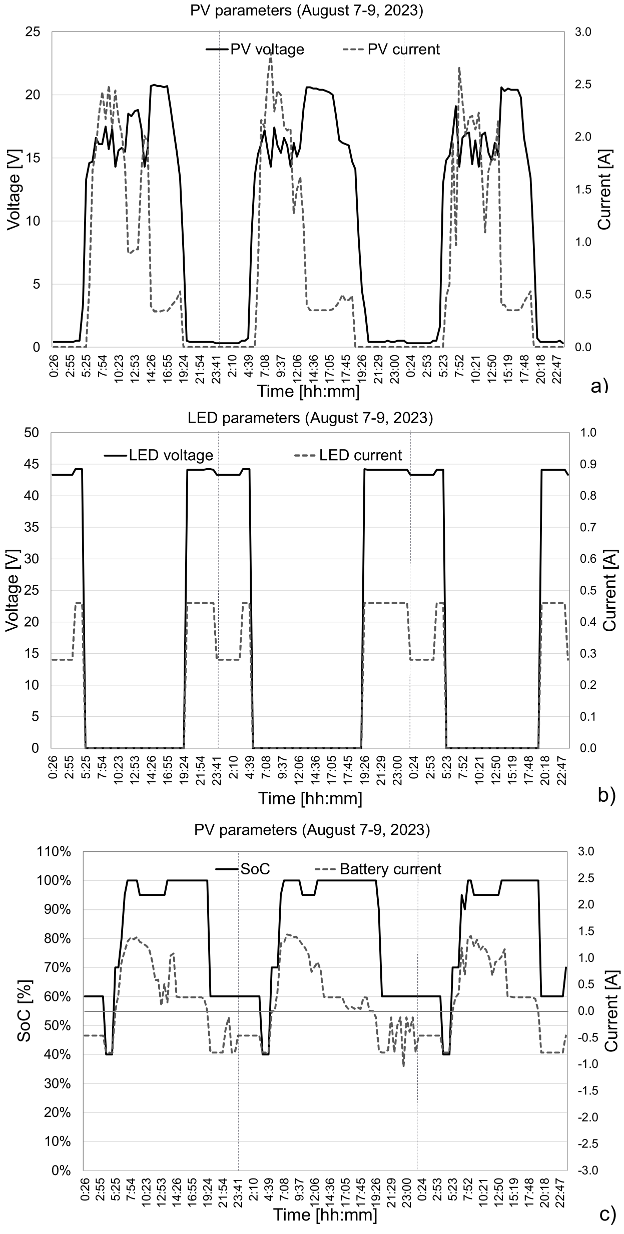


FIGURE 7. Electric parameters measured in August 7-9, 2023: a) PV voltage and current; b) LED lighting voltage and current; c) SoC and battery current.

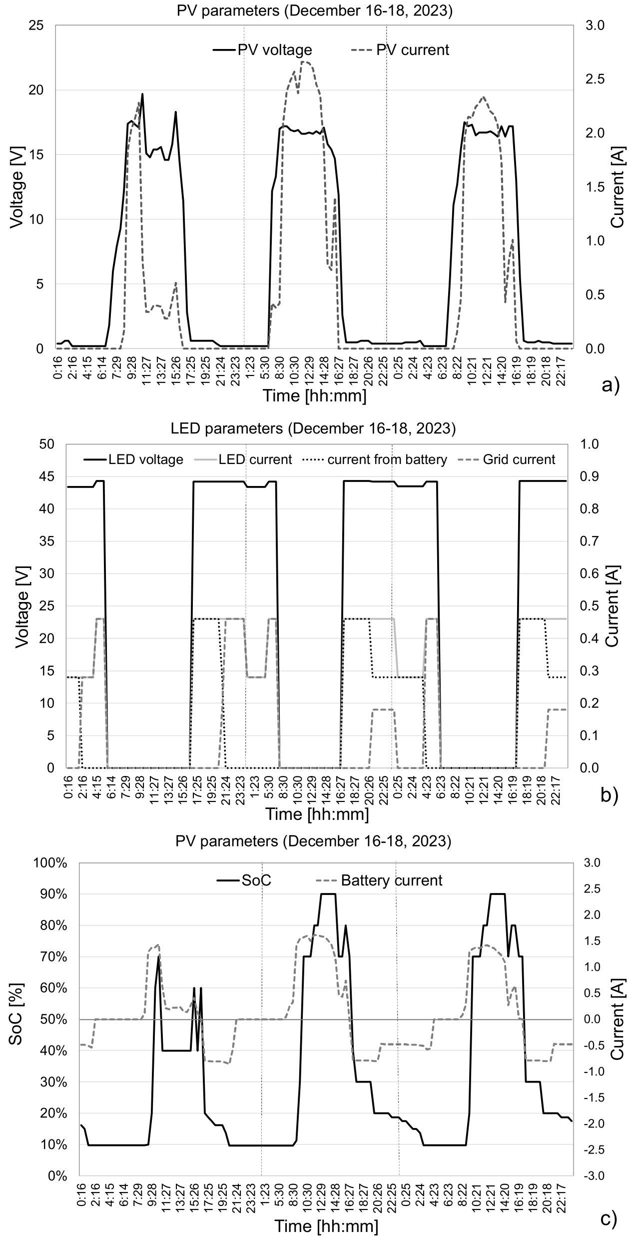


FIGURE 8. Electric parameters measured in December 16-18, 2023: a) PV voltage and current; b) LED lighting voltage and current; c) SoC and battery current.

of their sunny hours. The predicted annual PV production is equal to 71 kWh in Perugia (real condition recorded in 2023-2024), 63 kWh in Bolzano, and 83 kWh in Catania (the tool uses the average weather data of more than 10 years for BZ and CT). In Table 1 the annual data obtained from the tool are reported. The consumptions of the LED lamp are lower in CT (-15%) and higher in BZ (about + 9% with respect to Perugia): they are in line with the on period of the streetlamp (3370, 3780, and 4100 hours per year for Catania, Perugia, and Bolzano, respectively). The energy taken from grid in a year is 43-46% for BZ and PG, only the 35% for CT. The number of hours in which the lamppost is not self-sufficient decreases for CT (1080 that are only the 32% of the total hours of the on-period) and they increase for BZ (1910 hours of a total value of 4100, the 46%).

This tool is useful for a forecasting the performances of streetlamps installed in different case studies. The model allows the analysis of the benefits gained from replacing all the lamps on the pedestrian path with the proposed solution (see Table 2). Ten high-pressure sodium streetlamps installed along the walkway are responsible of a yearly electricity consumption variable between 4080 and 4960 kWh per year in the selected locations: the replacement of the streetlamps

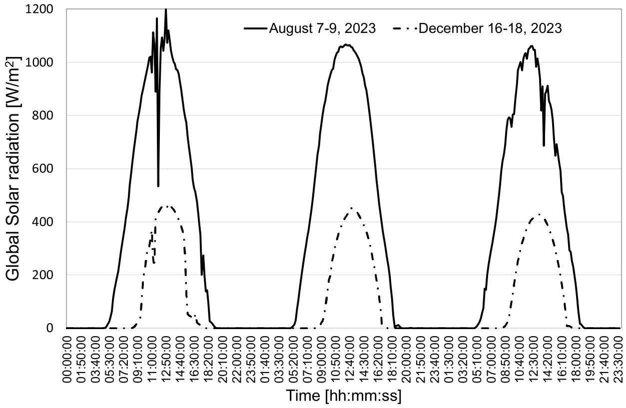


FIGURE 9. Comparison between the global solar radiation on horizontal plane in summer and winter.

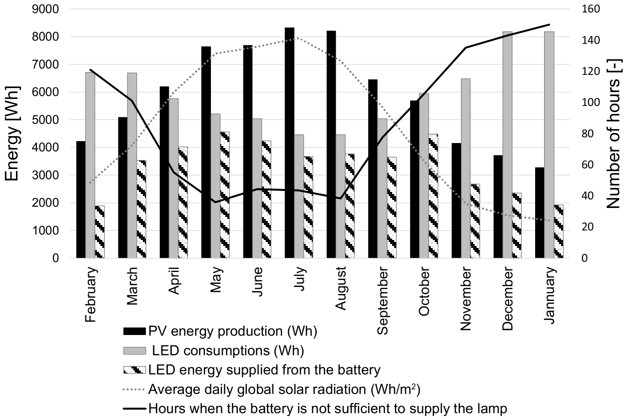


FIGURE 10. Annual energy analysis of the PV-based lighting system.

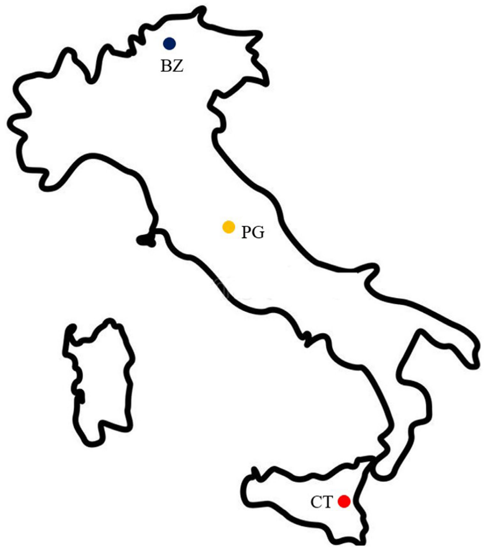


FIGURE 11. Italy map and positioning of the different sites: Bolzano (BZ) in north Italy, Perugia (PG) in Italy center, Catania (CT) in the south.

with the novel PV-based lamp allows an annual energy saving variable in 93-95% range.

TABLE 1. Results of algorithm application in different locations (single solar streetlamp).

City	Average global solar radiation (kWh/m^2 year)	PV energy production (kWh/year)	LED consumptions (kWh/year)	Energy from grid (kWh/year)	Number of hours the battery is not sufficient
Bolzano	51.9	62.8	78.5	36.4	1910
Perugia	56.7	70.7	72.2	31.4	1670
Catania	60.2	83.3	61.1	21.7	1080

TABLE 2. Pedestrian path scenario before and after the replacement of the lamps with the proposed novel solution.

City	Electricity consumptions BEFORE (kWh per year)	Electricity consumptions AFTER (kWh per year)	Energy Saving (%)
Bolzano	4961	363	93
Perugia	4522	314	93
Catania	4080	217	95

C. ECONOMIC AND ENVIRONMENTAL CRITICAL ANALYSIS

A technical-economic analysis is finally proposed by authors. The annual costs savings obtained when the novel PV-based lamps are installed in place of the standard high pressure sodium streetlamp are 464 € for Catania, 505 € for Perugia, and 552 € in Bolzano but the initial investment is very high, considering the significant cost of the lampposts. Moreover, it is also necessary to consider the service costs of the solar streetlamps due to the maintenance of the different components (above all for PV cells) and the substitution of the lithium-based batteries. Nevertheless, the PV-based luminaries have a lifetime longer than 15 years; on the contrary, the high-pressure sodium lamppost should be substituted at least 2 times along the 15 years due to the lower lifetime of lamps (24000 hours). In these conditions, it is possible to analyze the cash flow shown in Figure 12. The yearly costs savings due to the use of the novel solar streetlamps are not so high to cover the great investment every year (about 50 €/year for every lamp) but the important expenditures intended at 7th and 14th years for CT (at 6th and 12nd years for BZ and PG) allow the achievement of the costs balancing. In particular, the PbT (Payback Time) of the investment is 11-12 years for Perugia and Bolzano and 13-14 years for Catania. The Net Present Values (NPV) at the end of the lifetime is minimum for CT (5200 €) and maximum for BZ (6130 €): even if the PV solar cells are more efficient in south regions it is necessary to consider that in the southern Italian cities the number of sunny hours are higher, and the on-period of the lamppost is reduced.

The proposed solution is not so advantageous due to its expensive costs that are expected to decrease in the future years. Nevertheless, it should not be neglected the costs of electricity taken from the grid (single national price named PUN in Italy). The value chosen for this scenario is quite low

(120 € /MWh) and it is the cost for purchasing electricity observed in January 2024 in Italy in F2-F3 time bands (evening and night). The PUN tariff has showed significant fluctuations in the last three years (Figure 13) and it is expected to vary again in the future.

The same scenario is, therefore, analyzed also when the cost of electricity increases up to 550 € /MWh (constant for 15 years) (Figure 14) and for a mean value of 180 € /MWh (constant for 15 years) (Figure 15). It is interesting to observe that for the most onerous scenario PbT is only 5-6 years for BZ and PG, 6-7 years for CT with NPV in the range 22000 – 27000 €. An intermediate situation is observed for a mean value of PUN equal to 180 € /MWh: the PbT is the same of the current scenario (Figure 12) but the Net Present Values increase up to 7600 – 9000 €.

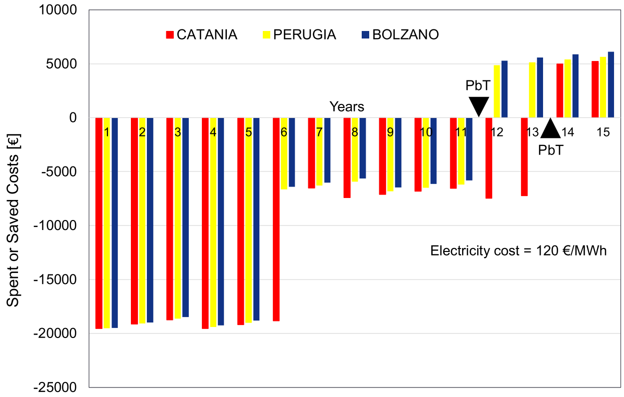


FIGURE 12. Cash flow of the investment for PV-solar streetlamps installation in the pedestrian path (scenario January 2024).

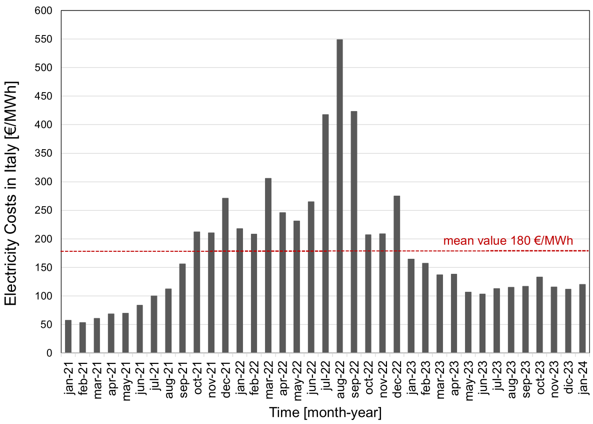


FIGURE 13. Italian trend of the single national price for electricity (named PUN in Italy) for time bands F2-F3 (evening-night).

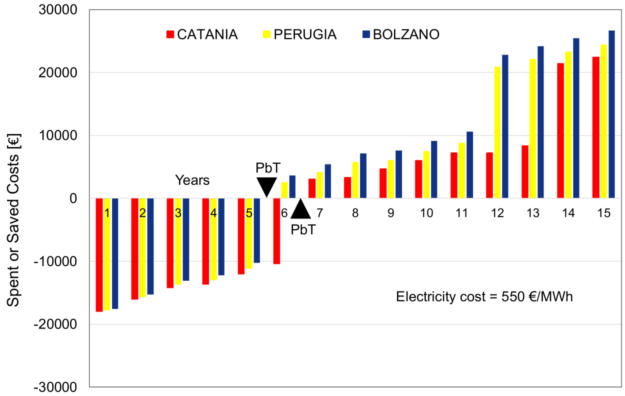


FIGURE 14. Cash flow of the investment for PV-solar streetlamps installation in the pedestrian path (scenario for maximum electricity costs).

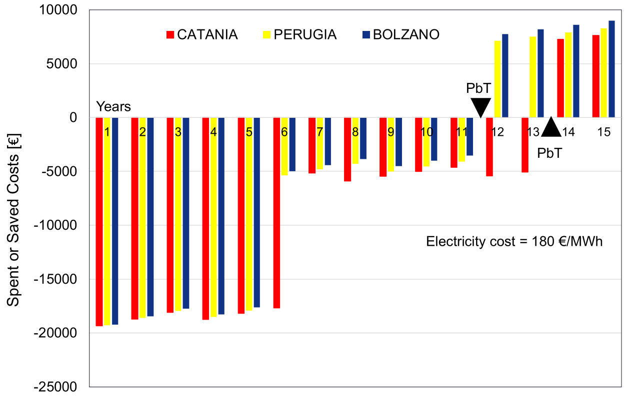


FIGURE 15. Cash flow of the investment for PV-solar streetlamps installation in the pedestrian path (scenario for a mean electricity cost related to 2021-2023 period in Italy).

Finally, it is possible to conclude that the solar streetlamp can be considered an interesting solution when an existent "old generation" lighting plant should be replaced, not only for the decreasing of the consumptions but also for the reduction of environmental impact. When considering an Italian carbon factor equal to 389 g CO_{2eq}/kWh (2023) [21], [22], every solar streetlamp can avoid 1560 kg CO_{2eq} (Catania), 1700 kg CO_{2eq} (Perugia), and 1856 kg CO_{2eq} in Bolzano at the end of its lifetime period.

IV. CONCLUSION

Solar-powered streetlamps are an energy-efficient alternative to traditional lamps in areas where high illuminance values are not required. They are particularly suitable for replacing outdated lamps in zones of the city where safe pedestrian and cyclist transit, as well as well-lit road conditions, are crucial. This work examines the annual performance data of a PV-integrated lighting system installed in Italy. The proposed solution is located along a pedestrian path and it is compared to nine traditional streetlamps in the surrounding green area (high-pressure sodium lamps). The novel streetlamp is programmed to maintain minimum illuminance values expected for pedestrian road type P2 (with a reduction of the power in the central hours of the night). The electricity parameters are analyzed in selected days in different seasons and the energy performances of the system is examined every month. The measurements indicate when the PV power is insufficient to power the lamp and the system must draw power from the grid. It is observed that the annual energy consumptions are only 72 kWh (57% is supplied from the battery and about 43% is taken from the grid). An algorithm for the simulation of the energy performance of the PV-integrated lamp is developed in Python programming language based on the yearly measurements. It is used to analyze the performance of the proposed solution in other locations and for different boundary conditions. Three scenarios are simulated to observe the same case study in Italy north, center, and south. The energy taken from grid in a year is 35-46% of the total required energy.

Economic and environmental analysis conclude this research work: it calculates the energy savings achieved by replacing traditional high-pressure sodium lamps with the new solar lamppost in three selected Italian locations. The same cash flow analysis is carried out in a lifetime scenario of 15 years for different PUN values of Italian market: it is possible to say that the expensive cost of the innovative solar streetlamp does not consent to have acceptable payback times (11-13 years) when the PUN values are low (120-180 € /MWh) with net present values of about 5000 – 9000 €. When the electricity cost is high (up to 550 € /MWh) the PbT is 5-7 years. Moreover, the solar lamppost is also more efficient in central and north regions because the expected on-period of the lamps is lower in south with consequent lower energy savings.

Added considerations are also commented with respect to environmental impact: every streetlamp can avoid 1600 – 1900 CO$_{2eq}$/kWh at the end of its useful life.

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