

Comparative study of the public lighting using a conventional and solar energy-case of a region in Agadir

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ABSTRACT

In this paper, we focus on the optimization of electric energy consumption in public lighting of a region in Agadir proposing the integration of renewable energy sources, especially the photovoltaic (PV). Two models have been adopted, simulated and compared with experimental results under the MATLAB/Simulink environment. The first model is devoted to the simulation of the conventional street lighting in the area supplied by the “Substation 9” in Dcheira El Jihadia in Agadir city, while the second model provides modeling and simulation of the PV powered public lighting system, as an alternative for the street lighting in the testing area. The results of simulation show that the solar street lighting system is much more economical and, moreover, it is inexhaustible and non-polluting compared to the classic street lighting.

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1. INTRODUCTION

Street lighting system is one of the major energy consumption in the world and it is one of the most important needs in our daily lives. The public lighting accounts for a significant share of the energy consumption of the municipalities and of the entire country. With the liberalization of the electricity market and the sharp rise in energy costs charged to municipalities, the public lighting has become a major issue. In many municipalities, the energy consumed by street lighting accounts for the highest share of their annual electricity bill; for example, around 80% of the budget in the municipality of Agadir.

As a source of comfort and productivity, public lighting contributes to the quality of life and attractiveness of municipalities and cities. Yet the quality of lighting, in terms of light stability and continuity of service, depends on the quality of the electrical energy consumed. The power supply for street lighting networks has therefore become increasingly important due to the decrease in available non-renewable resources and environmental problems. As a result, many renewable power generation plants, such as wind, photovoltaic (PV), hydroelectric plants, and fuel cells, are connected to the distribution grid [1]–[8].

In fact, a study is being conducted in Hungary [9] to show the savings to be generated by installing PV systems and light emitting diodes (LED) lamps in street lighting. It concerns all the villages in the country that are lit by 229 light points. This study, carried out over a 20-year period, demonstrated that the solar

powered public lighting allows energy savings of up to 60%, and the smart street lighting offers up to 70% energy savings compared to conventional public lighting system.

Within this context, we recommended public lighting optimization measures [10], [11] to minimize energy consumption and reduce the municipality's energy bill. These recommendations were made after gathering preliminary knowledge in the field and carrying out an inventory.

The present paper is organized as follows: after this introduction, we present in section 2 the tools of investigation and the inventory of street lighting in the area supplied by the "Substation 9". Then, in sections 3 and 4, we describe the public lighting models of the testing area, namely the conventional street lighting model and the PV based public lighting model. Then, the simulation results will be presented, compared with the measurements and discussed in section 5. Finally, conclusion in section 6.

2. CONTEXT AND TOOLS

2.1. Work context

Our investigations began with an analysis of the state of the street lighting substation, named "Substation 9", in the Dcheira El Jihadia municipality. This analysis revealed significant renovation needs. Indeed, at the beginning of our study, an exhaustive inventory of the control cabinet components and light points is essential. Following this inventory, it allowed us to identify the number of lamps supplied by each feeder, as well as the total power demand of the feeders. Furthermore, the testing substation supplies four feeders as shown in Figure 1, the first of which serves 22 light sources with a total power of 7.8 KW. Then, 49 lamps are supplied by the second feeder with a power of 4.26 KW. Then, the third feeder serves 27 light sources with a total power of 5.76 KW. Finally, the last feeder supplies only 15 lamps with a power of 2.98 KW. Table 1 summarizes the various types and powers of lamps used to illuminate the different areas. Most of the lamps used are high-pressure sodium (HPS).

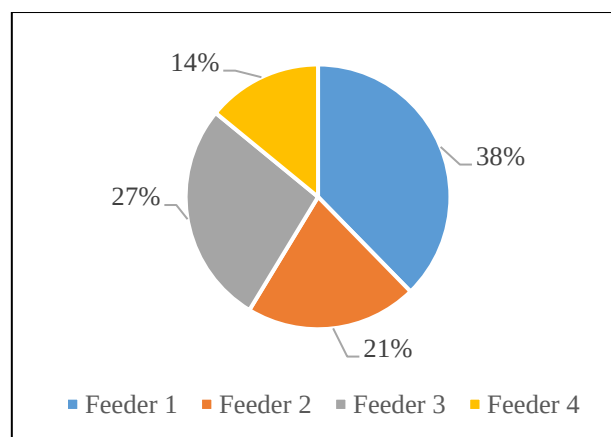


Figure 1. Distribution of public lighting feeders of "Substation 9" according to total power of the lamps

Table 1. Types and number of lamps supplied by the "Substation 9"

Designation	Feeder 1		Feeder 2				Feeder 3				Feeder 4					
Number	11	11	29	3	2	1	4	4	6	1	13	12	1	9	5	
Type	HPS		Economic		LED		HPS		MH		HPS		HPS			
Power (W)	400	250	36	70	100	150	70	150	250	150	70	150	250	70	150	250
Total	113															

2.2. Development tools

The tools used in this work for the development of the models and for carrying out the various simulations are:

- MATLAB/Simulink R2013a (8.1): for the development of PV street lighting models and their simulation.
- Dialux 4.12: for calculating optimum brightness in public lighting installation.
- PVsyst 6.4.3: for sizing the PV systems required for PV street lighting.
- PLECS Blockset 3.4.7: for the simulation of the conventional public lighting model.

3. MODELING OF CONVENTIONAL STREET LIGHTING

In order to design and predict the system to be implemented, based on PV panels, to provide public lighting in the testing area, it is essential to model the existing conventional street lighting system. For that purpose, as shown in Figure 2, we developed a simplified block diagram under Simulink, modeling the conventional public lighting. This diagram consists of the following 3 components: the transformer substation with its protection system, the light fixture, and the measurement system.

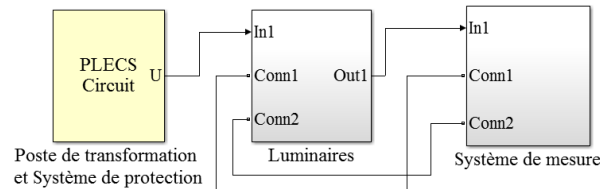


Figure 2. Simplified model of the conventional street lighting system of "Substation 9 El Jihadia"

3.1. Transformer substation and protection system

This section mainly consists of equipment containing one or more transformers in order to ensure the derivation of current on the network, the protection of the transformer on the high voltage type A (HVA), the high voltage/low voltage (HVA/LV 22,000V/230V) transformation, the protection of the transformer on the LV side, and the energy meter (Figure 3).

For protection purposes, all metal masses of the substation are connected to the earth ground. During maintenance or other interventions in the substation, the incoming lines must be disconnected and the interconnected cables must be grounded.

The simulated protection system aims to distribute electrical energy to the light points at appropriate times and in complete safety. This device ensuring the safety of users, operators as well as the equipment, is integrated into the control cabinet with a control device consisting of the metering equipment and an astronomical clock for controlling operating times.

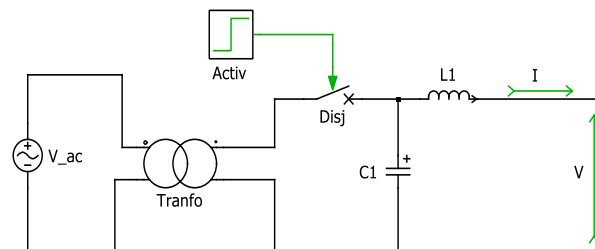


Figure 3. Electrical model of the transformer substation with a protection system

3.2. The light fixture

This part is also called a lantern. Its essential function is to emit, distribute and control the light provided by a light source, namely the lamp. The light fixture contains a ferromagnetic ballast, an ignitor, capacitors depending on the type of lamps used, and finally a lamp. The equivalent circuit of this light fixture is shown in Figure 4.

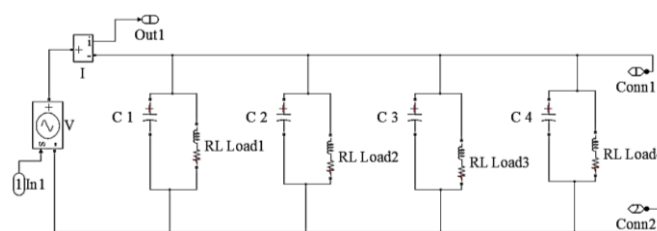


Figure 4. Equivalent model of the light fixtures

The light fixture have specific characteristics that are essential to any lighting project. Its main properties are described in Table 2 [12], [13]. The Table 3 summarizes the key characteristics of the capacitors associated with the light fixtures depending on the lamps powered by "Substation 9" [14].

Table 2. Types and properties of street lighting lamps implemented in the Dcheira El Jihadia city [15]

Type	HPS	Conventional	Metal halide	
			With ceramic arc tube	
Light efficiency (Lm/W)	47–150	54–120	55–95	
Economic lifetime (h)	12,000–16,000	4,000–8,000	4,000–8,000	
Temperature (K)	Standard Improved IRC 2,200	3,700–6,100	3,000–4,200	
Color rendering index (CRI) (%)	Standard–High flux 20 Improved IRC 65–80	65–93	83–93	
Control gear	Ballast or ballast and ignitor —	Ballast, ignitor High frequency electronic ballast	Ballast, ignitor High frequency electronic ballast	

Table 3. Characteristics of capacitors associated with light fixtures according to powers and types of lamps

Reference (μF)	Voltage (V)	Size (mm)	Power (W)		
			HPS lamp	Mercury lamp	MH lamp
10	250	Ø30/H70	70	125	70
20	250	Ø35/H94	150	250	150
32	250	Ø35/H135	250	400	250
50	250	Ø45/H135	400	1,000	400

3.3. Measurement of electrical consumption

The third part of the model in Figure 2, as shown in Figure 5, consists of devices for measuring quarterly electrical energy consumption in conventional street lighting system. Indeed, in the block diagram shown in Figure 5, the total power is defined by the product of the root mean square (RMS) value of the current, the voltage and the Power factor Ψ which is equal to 0.9, related to block "cte" in Figure 5. Then, the consumed energy is calculated by multiplying the total power by the operating period during one year as shown in Table 4. This is ensured by the "Stair" bloc which generates a signal corresponding to the number of lighting hours per quarter for 2 years.

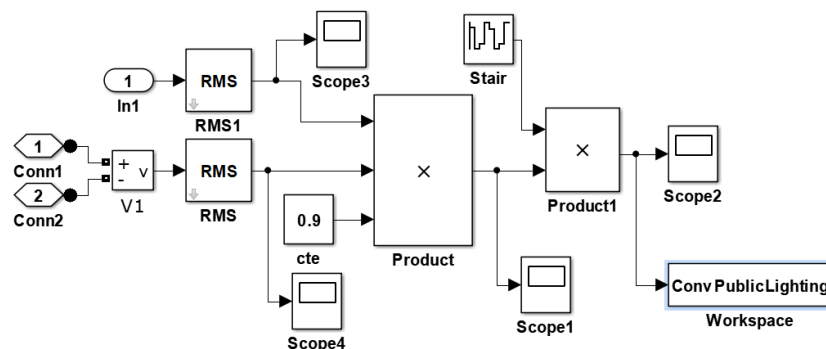


Figure 5. Electrical model of the measuring system

Table 4. Number of lighting hours per quarter during one year

Quarter of the year	1	2	3	4
Number of lighting hours (h)	1,189	985	1,032	1,240

The model developed above in Figure 5 can serve as a basis for comparison between a public lighting installation using a ferromagnetic ballast and one using an electronic ballast. The latter does not require a compensation capacitor, thus it contributes to an increase in the lamp lifetime, with a power factor greater than 0.9. Moreover, the efficiency of an electronic ballast can exceed 93%, whereas the average efficiency of a ferromagnetic ballast is only 85% [16].

4. MODELING OF PV SOLAR STREET LIGHTING

In order to confirm the possibility of replacing conventional public lighting with solar-powered lighting, we propose to study and simulate the power involved in street lighting powered by PV. Subsequently, we make a comparison with the actual energy consumption of the tested area. In order to model PV solar public lighting, we first need to choose suitable LEDs. This selection is made using the DiaLux 4.12 software.

The method is based on modeling the geometry of the area to be illuminated using DiaLux software. Next, the proposed LED lamp/light fixture, which offers higher light efficiency than a conventional lamp, is integrated into the model. The maintenance factor is then set to 0.8, this factor is proportional to the LED lamp's lifespan. Finally, the simulation is run to generate and validate the lighting design results. The LEDs thus chosen are described in Table 5 [17].

Table 5. Description of suitable LEDs replacing the lamps used in conventional street lighting

Replacement LEDs	55 W	130 W	200 W	300 W
Conventional lamp	HPS 70 W	HPS 150 W	HPS 250 W	HPS 400 W
Power (W)	55 against 80	130 against 169	200 against 276	300 against 433
Light efficiency (Lm/W)	115 against 79	122 against 93	145 against 105	167 against 115
Luminous flux (Lm)	6,300	15,800	29,000	50,000

The next phase is devoted to modeling, using MATLAB/Simulink software [18], the PV panel-based system to be implemented in street lighting. Moreover, the characteristics of the various components of the solar streetlight are summarized in Table 6, which includes the results obtained regarding the sizing of a 55 W PV streetlight with an average of 11 hours of public lighting per day [19].

Table 6. Sizing results using PVsyst for the PV installation replacing the public lighting of "Substation 9"

Daily energy needs	0.605 KWh
Selected PV module	Model: poly 80 Wp 36 cells Type: polycrystalline Quantity: 1 module Nominal power: 80 Wc Vmpp: 18.1 V Imp: 4.42 A Voc: 22.6 V Isc: 4.68 A Number of cells in series: 36 Open-circuit temperature coefficient: -74.4 mV/°C Short-circuit temperature coefficient: 2.8 mA/°C
Chosen battery	Type: GEL/12 Quantity: 1 battery Nominal capacity: 120 Ah

Figure 6 illustrates the developed model equivalent to the PV solar public lighting system to be implemented for the "Substation 9" in Dcheira El Jihadia in Agadir. The model shown in Figure 6, which will be simulated further below, comprises the three main components described.

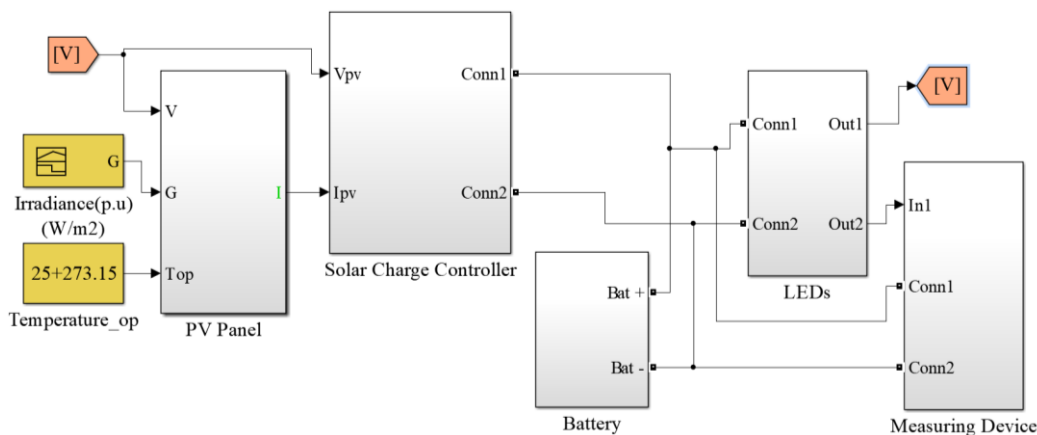


Figure 6. Equivalent model to the PV powered street lighting in the testing area

4.1. The photovoltaic source

This module constitutes the renewable source, especially the PV. At the input of the PV panel model, we need the irradiance G (in W/m^2) as shown in Figure 7, equivalent to the amount of light received per unit area (W/m^2), and the ambient temperature T was set to a fixed value of 298.15 K. At the output of the PV module, we have the generated current I [20], [21]. Figure 8 shows the equivalent electrical diagram of a PV cell.

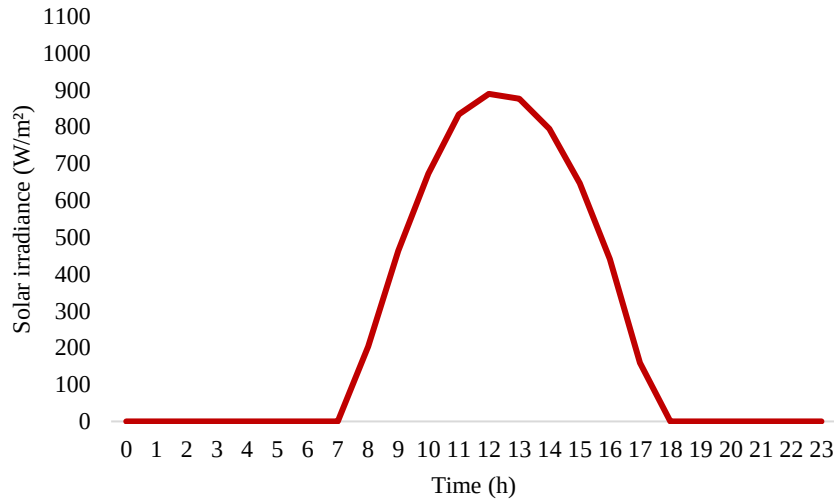


Figure 7. Day evolution of solar irradiance in the testing area

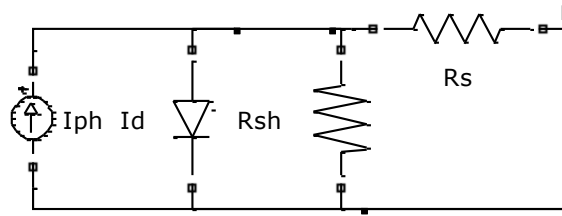


Figure 8. Equivalent block diagram of the PV cell

The mathematical equations governing the operation of the PV panel, consisting of 36 cells connected in series, are given by the following system of equations:

$$\left\{ \begin{array}{l} I = I_{ph} - I_d - \left(\frac{V_d}{R_{sh}} \right) \\ V_{pv} = V_d - IR_s \\ I_{ph} = (I_{phn} + k_i \Delta T) \left(\frac{G}{G_n} \right) N_{pv} \\ I_d = I_0 \left[\exp \left(\frac{V_d}{V_T} \right) - 1 \right] N_{pv} \\ I_{phn} = I_{scn} \left(\frac{R_s + R_{sh}}{R_{sh}} \right) \\ I_0 = \frac{(I_{scn} + k_i \Delta T)}{\left[\exp \left(\frac{V_{ocn} + k_v \Delta T}{V_T} \right) - 1 \right]} \\ V_T = a N_s K \frac{T}{q} \\ \Delta T = T - T_n \end{array} \right. \quad \left\{ \begin{array}{l} R_{sh} = 350 \, \Omega \\ R_s = 0.359 \, \Omega \\ k_i = 2.8 \, \text{mA/K} \\ k_v = -74.4 \, \text{mV/K} \\ q = 1.6 \times 10^{-19} \, \text{C} \\ G_n = 1000 \, \text{W/m}^2 \\ N_s = 36 \\ N_{pv} = 1 \\ I_{scn} = 4.68 \, \text{A} \\ V_{ocn} = 22.6 \, \text{V} \\ a = 1.3 \\ K = 1.38 \times 10^{-23} \, \text{J/K} \\ T_n = 298.15 \, \text{K} \end{array} \right.$$

4.2. The battery

Among the countless ways to store the energy produced by a PV generator throughout the day, batteries are considered economically and technically accessible. This storage system is necessarily placed between the PV generator and the LED, as the power supply for the street lighting system comes mainly from the battery during the night. The load profile is illustrated in Figure 9.

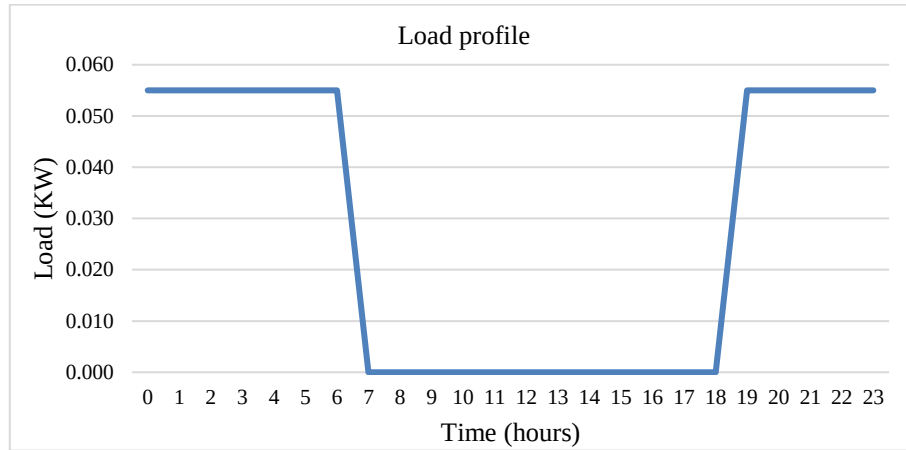


Figure 9. Load profile

At the input, we have the current I_{pv} generated by the PV module and the voltage V_{pv} between its terminals. At the battery's output, the current I_{out} and voltage V_{out} supply the load, which consists of an LED. The equivalent model of this battery is shown in Figure 10.

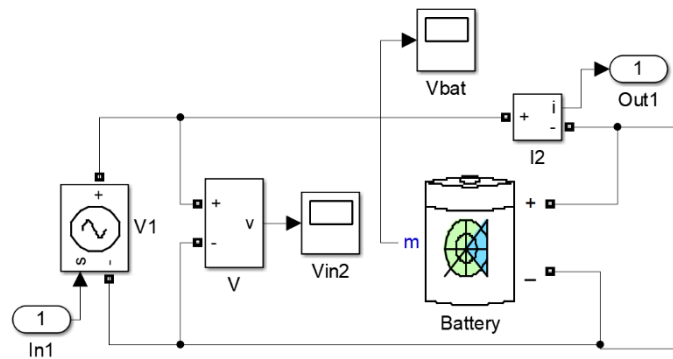


Figure 10. Equivalent model of the battery

4.3. Solar charge controller

In our study, we chose to use a series regulator, which serves as a protective element for the battery. In fact, the system illustrated in Figure 11 includes a buck DC-DC power converter, controlled using the principle of pulse width modulation (PWM). This chopper is modeled by the equivalent electrical diagram shown within the dotted frame in Figure 11 [22].

4.4. Light emitting diodes

After the three components described above related to the PV powered public lighting, the final link in the chain is introduced. This final element is the one that provides illumination via LEDs. Its key performance advantages compared to conventional lamps include high irradiance, long lifespan, enhanced luminous efficiency, and energy-saving capabilities [6]. The corresponding model of these LEDs is given in Figure 12.

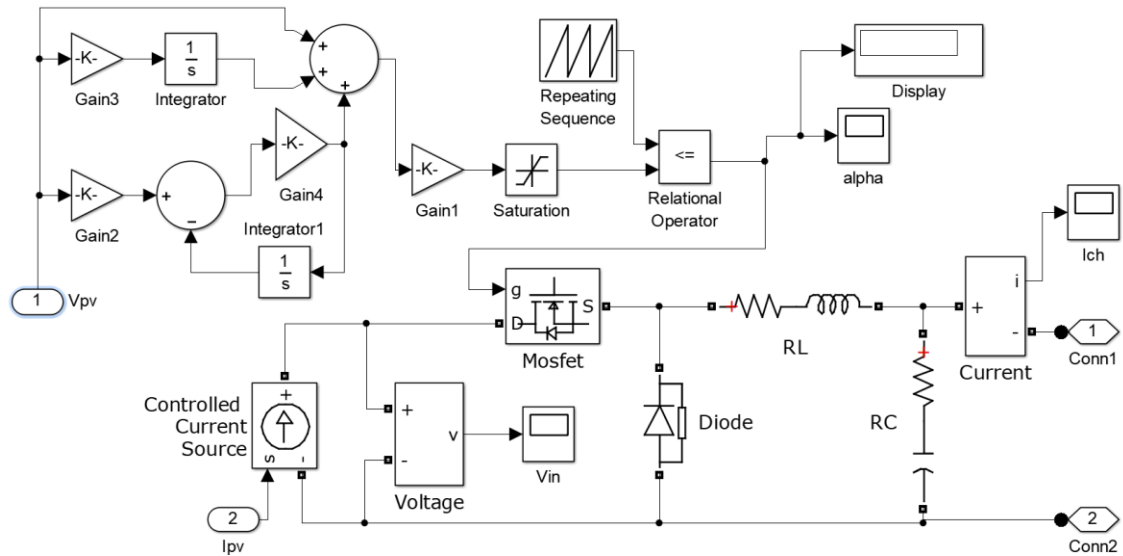


Figure 11. Equivalent electrical circuit to the solar charge controller

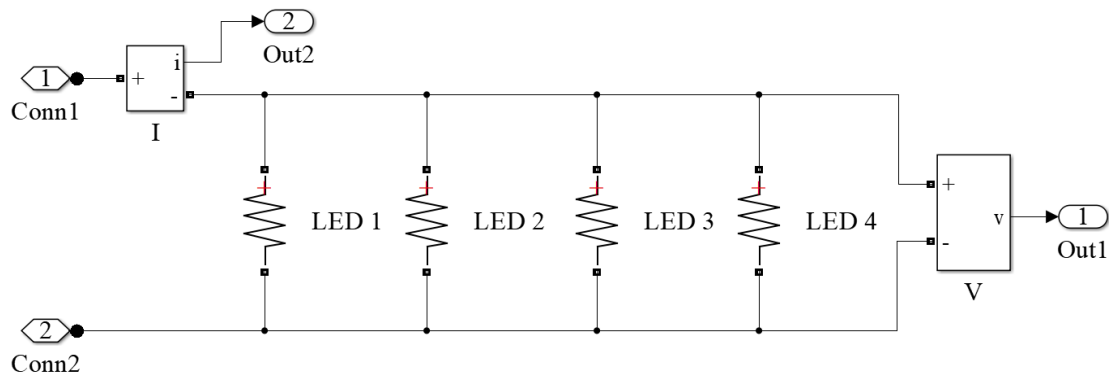


Figure 12. Electrical model of the chosen LEDs

4.5. Measurement of electrical consumption

The last part of the model in Figure 6, as illustrated in Figure 13, comprises the various devices used to measure the annual electrical energy consumption in PV solar street lighting. The energy consumed is defined as the product of the total power and the operating period over one year. This function is ensured by the "Stair" bloc. Moreover, the total power is determined by multiplying the RMS value of the current and the voltage.

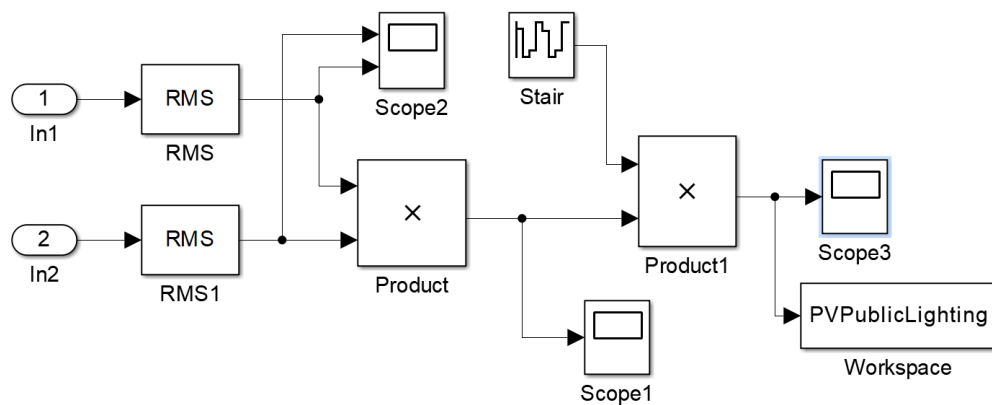


Figure 13. Electrical model of the measuring devices

5. RESULTS AND DISCUSSION

The different models of conventional and PV solar street lighting system presented above, as well as their simulations, have allowed us to identify the quarterly energy consumption curve. These simulation results, as shown in Figure 14, are compared with the actual billed electricity consumption of "Substation 9" in Dcheira El Jhadia in Agadir city. The actual consumption data were collected based on billing records from 2015, as illustrated in Table 7.

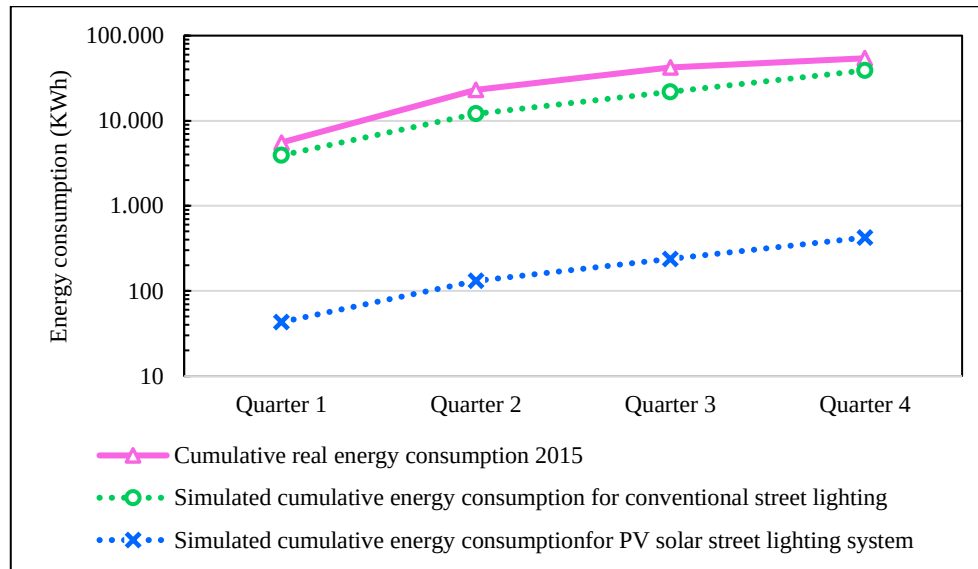


Figure 14. Actual energy consumption compared to simulations for PV and conventional street lighting of the "Substation 9 El Jhadia"

Table 7. Quarterly consumption data of street lighting of the "Substation 9 El Jhadia"

Electric energy consumption	Quarter 1	Quarter 2	Quarter 3	Quarter 4
Cumulative real energy consumption (KWh)	5,547	17,433	19,206	12,016
Simulated cumulative energy consumption for conventional street lighting (KWh)	3,922.08	12,052.32	21,820.37	38,944.02
Simulated cumulative energy consumption for PV solar street lighting system (KWh)	43.11	131.54	237.78	424.02

Following the studies presented above, as shown in Figure 14, we observe that the actual consumption (pink curve) is higher than the conventional energy consumption (green curve) simulated under MATLAB/Simulink. This discrepancy is due to the existence of an additional load supplied by the "Substation 9 El Jhadia": the mosque. However, still according to the results in Figure 14, the simulated energy consumption in PV solar public lighting (blue curve) is significantly lower than that of conventional street lighting system, since PV LED lamps are more efficient than HPS lamps in terms of light efficiency, lifespan and maintenance cost, as illustrated in Table 8.

Table 8. Comparison between PV LED lamps and HPS lamps

Type of lamps	Light efficiency (lm/W)	Lifetime (h)	Maintenance cost
PV LED lamp	150–180	50,000–100,000	Low
HPS lamp	47–150	12,000–24,000	High

5.1. Energy and financial gains

The annual energy savings are calculated as the difference between the annual energy consumption of the conventional installation of the "Substation 9 El Jhadia" (54,200 KWh) and that of the PV system (16,300 KWh). This result is then divided by the energy consumed by conventional street lighting (54,200 KWh), giving an energy saving of approximately 70%, as shown in Table 9.

Table 9. Energy and financial gains obtained for the "Substation 9"

Energy and cost savings data	Conventional street lighting	PV powered public lighting
Annual consumption (KWh)	54,200	16,300
Annual cost (MAD)	60,200.48	18,104.57
Annual energy and cost savings (%)		70
Annual energy savings per lamp (KWh)		355

The key indicator for annual energy savings per lamp is calculated by multiplying the total power of the conventional light fixture (70 W+10 W) by the number of lighting hours per year (4,446 h); the result is then divided by 1,000, which gives 355 KWh/lamp/year.

5.2. Ecological gain

CO₂ emissions are calculated using the emission factor for electricity, which is 0.705 Kg CO₂/KWh. Solar-powered street lighting provides a 70% reduction in CO₂ emissions compared to conventional public lighting for the "Substation 9 El Jihadia", as shown in Table 10.

Table 10. Ecological gain obtained for the "Substation 9"

Key parameters of ecological gain	Conventional street lighting	PV powered public lighting
Annual consumption (KWh)	54,200	16,300
Emission factor of CO ₂ (Kg CO ₂ /KWh)		0.705
CO ₂ total emission (Kg CO ₂)	38,211	11,491.5
CO ₂ emission reduction (Kg CO ₂)		26,719.5
Ecological gain (%)		70

5.3. Payback period

In order to determine the payback period for the PV powered street lighting of "Substation 9 El Jihadia", we have to calculate the first parameter which is the initial investment [23]. The initial investment cost is defined as the sum of the acquisition cost and the labour cost for the installation. The cost of equipment of the PV system is about 1,349,480 MAD, while the labour cost is approximately 8,475 MAD. Whereas the price of the components of the conventional installation did not exceed 618,290 MAD, with a labour cost of the installation of approximately 25,425 MAD as shown in Table 11.

Table 11. Payback period for the "Substation 9"

Costs data	Conventional street lighting	PV powered public lighting
Cost of equipment (MAD)	618,290	1,349,480
Labour cost (MAD)	25,425	8,475
Initial investment cost (MAD)	643,715	1,357,955
Annual cost of energy consumption (MAD)	88,080	48,415
Annual energy savings (MAD)		88,080
Annual operating cost (MAD)	87,450	26,950
Annual operating savings (MAD)		60,500
Annual cost savings (MAD)		148,580
Payback period (years)		9

The second parameter is the annual cost of energy consumption which is the product of total power of the lamps by the lighting hours per year (4,446 h) and the price of the Kilowatt-hour (1.11071 MAD). This average annual cost for the conventional installation is about 88,080 MAD. In the case of PV system where consumption is free, the equivalent of annual cost is about 48,415 MAD.

The last parameter is the annual operating cost which includes the annual cost of energy consumption and the annual cost of maintenance related to replacement cost. The conventional system has generated a significant cost of about 87,450 MAD. On the contrary, the operating cost for the PV system is only 26,950 MAD corresponding only to the annual cost of maintenance. Finally, the payback period, which is defined as the ratio between the initial investment cost and the annual cost savings [24], [25], is equal to 9 years for the testing area as shown in Table 11.

According to the Figure 14, and Tables 9 to 11, we observe that the PV street lighting system offers up to 70% energy savings compared to the conventional system; and also allows for a 70% reduction in CO₂ emissions related to the sustainable development goal 13 (SDG13).

All these key indicators will help municipality make a decision regarding the implementation of this PV installation and, consequently, to fundraising, as this PV installation aligns perfectly with the national sustainable development strategy and directly addresses several UN sustainable development goals (SDG7,

SDG11, SDG13, and SDG 9), in order to reduce the initial capital investment and thus minimize the payback period, which is approximately 9 years.

6. CONCLUSION

The investigations presented in this paper have allowed us to compare the energy consumed by conventional street lighting system with the predicted energy consumption if it were replaced by PV solar public lighting for "Substation 9" in Dcheira El Jihadia in Agadir city. According to the expected results, we can then confirm that the integration of renewable energy sources, such as PV, in street lighting system is much more economical with Annual energy and cost savings of about 70%; and, moreover, it is inexhaustible and non-polluting allowing a 70% reduction in CO₂ emissions. In perspective, a smart street lighting control system using machine learning-based optimization will be developed.

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AUTHOR CONTRIBUTIONS STATEMENT

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C : **C**onceptualization

M : **M**ethodology

So : **S**oftware

Va : **V**alidation

Fo : **F**ormal analysis

I : **I**nterpretation

R : **R**esources

D : **D**ata Curation

O : Writing - **O**riginal Draft

E : Writing - Review & **E**dit

Vi : **V**isualization

Su : **S**upervision

P : **P**roject administration

Fu : **F**unding acquisition

CONFLICT OF INTEREST STATEMENT

Authors state no conflict of interest.

DATA AVAILABILITY

Derived data supporting the findings of this study are available from the corresponding author, FO, on request.

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