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Optimization of multi-period investment planning in street lighting systems by mixed-integer linear programming

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Abstract. This article proposed the use of multi-period mixed-integer linear programming method for investment planning to support decision-making processes in upgrading and managing street lighting systems. The technique incorporates a multi-variate model that maximizes energy-saving by considering budget constraints, the state of the lighting system, and the available technology in the market to replace the existing streetlights. This topic is novel because the complexity of the problem relies on the existence of several potentially large investments. As explained in this paper, the proposed method optimally considers the investments and returns as a combination that maximizes energy savings. The method was tested using actual data from an undisclosed public lighting system in Colombia. The results obtained revealed that multi-period investment optimization based on mixed-integer linear programming is an ideal investment plan, particularly in streetlight systems. Therefore, it forms an invaluable tool for street lighting systems' administrators and decision-makers in optimizing and facilitating the critical decision-making process in their work environment.

Keywords: Energy efficiency / mixed-integer linear programming / upgrade / resource allocation

1 Introduction

Research on increasing energy efficiency has gained momentum along the current trends in sustainable development goals (SDGs) like affordable clean energy, reducing inequalities, poverty eradication, and global warming [1]. For example, Intergovernmental Panel on Climate Change (IPCC) report explained that energy savings contribute towards energy access, sustainable energy production, energy access, innovation, and the development of sustainable cities. This results in new decent job opportunities in firms whose services are geared toward energy efficiency. As IPCC further expounded [1], among the interventions devised to achieve energy efficiency are using energy-efficient appliances in households, energy-intensive industries, and behavioral approaches emphasizing a deeper understanding of energy management, consumption drivers, and absolute reduction barriers.

According to the International Energy Agency (IEA), it is recommended to prioritize energy efficiency in buildings, appliances, lighting, transportation, industry, and public energy services. In its 2020 study, IEA found that energy efficiency—as measured by primary energy intensity—has been declining significantly across the globe due to falling energy prices and the detrimental impact of the Covid-19 pandemic [2]. Although there were slight improvements in 2018 (1.5%) and 2019 (1.6%), only 0.8% was projected in 2020. As the research further revealed, these improvements are far from the required levels to achieve sustainability and global climate goals. This was a great cause for concern since energy efficiency promotes the reduction of greenhouse gas emissions-related energy in the next 17 yr [2]. However, the 2022 report by IEA revealed an increase in energy efficiency of 2%, with the energy demand across the globe falling to 1% from the previous year's significant 5% increase [3]. With efforts to improve energy consumption, the year's improvement in energy intensity cannot be perceived as a 100% achievement because there is a neighborhood of 2.5 billion people without access to reliable, clean cooking, heating, and energy services [3].

The street lighting sector represents about 3.19% of the energy consumed globally; specifically, in Colombia, this value equals 3%, equivalent to 2.122 GWh [4]. For these reasons, it is relevant to execute projects that improve the energy efficiency of street lighting systems. In this context, some of the relevant projects established to modernize the existing public lighting system by replacing old streetlights with LED luminaires are listed below:

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– New York City (USA) aims to change 500,000 street-lights from street lighting to LED by 2025 [5].
– The autonomous city of Buenos Aires (ARG) achieved its goal of changing more than 158,000 streetlights by 2019, becoming the first capital of Latin America with 100% LED [6].
– Bogotá (COL) was committed to finishing the replacement of 150.000 LED streetlights by the end of 2019 [7].

Due to their public nature, the management of street lighting systems involves technical, social, environmental, and economic features that add complexity to the decision-making process regarding the investments to be performed by the system administrator [8–10]. For instance, street lighting systems cover large metropolitan areas and, their refurbishment involves significant capital investments, usually from public entities or, in some cases, from distribution utilities [9]. Therefore, energy management experts mainly consider valuable tools and techniques to support decision-making and design suitable investment strategies for upgrading existing systems [11].

In this regard, from our literature review on proposals to improve energy efficiency by street lighting optimization, we determined three typically applied approaches for optimization, and each has been expounded in the next three paragraphs.

The first aims to revamp energy efficiency by modifying the lighting designs [7]. This is achieved by selecting the most appropriate combination of various design parameters such as distance between the lights, mounting height, angle of inclination, the advance of the streetlight assembly over the road, road width, technology type, and streetlight photometry [7,12].

The second involves designing control algorithms for intelligent lighting. Each light requires a control device that allows auto-management to apply the algorithms. In addition, an appropriate number of sensors are strategically placed to collect data regarding the state of the streets at any particular time. As a result, the lighting systems are designed to autonomously and intelligently operate in real-time, dimming and brightening each streetlight according to the requirements [13].

Finally, optimization models are developed based on the written algorithms. This line of research assumes that the existing lighting design complies with the intended regulations. The problem here lies in modifying or replacing existing technologies efficiently to improve performance indicators. The energy efficiency of the whole system is one of the indicators.

Referring to the optimization models, a multi-objective optimization was recently proposed in [14]. The optimization is based on three objectives. The first one corresponds to minimizing light pollution, the second seeks to maximize the color reproduction index (CRI), and the third objective maximizes energy savings [14]. Regarding objectives one and two, it has been observed that if the lighting system is upgraded by LED technology, such objectives lose meaning. This is due to the fact that LED lamps do not reflect light beams toward the atmosphere due to their constructive design that makes them focus light in a very concentrated direction [12]. In addition, LED lights are advantageous due to their high CRI compared to high-pressure sodium (HPS) streetlights. This guarantees that the user will receive the necessary comfort.

Additionally, a single period for the optimization is considered in [10], solving the problem for medium-term planning (one year). In general, a public lighting system administrator annually accounts for capital for investments. However, it becomes convenient to plan the system upgrade for the whole duration of the administration, like four or five years, implying that the problem can be considered as one of long-term planning [15,16].

Based on the literature above, this article proposes an optimization methodology based on mixed-integer linear programming (MILP), with multiple periods, considering a single objective to maximize energy savings. This methodology is the most appropriate in this context because it allows for assessing investments in different technological alternatives that are available in the market—various manufacturers—by considering the energy consumption of each option and the cost. As a result, starting the analysis from the current state of the public lighting system, the optimization method will provide an optimal investment plan for each period by aiding managers in the calculation of the capital required to modernize the streetlight fleet completely.

2 Formulation of the optimization problem

The multi-period optimization model's aim is to identify the optimal investment strategy, indicating the upgrading actions, j, that must be executed for each period t, with $t = 1, 2... T$. It is important to note that X_j is the decision variable, entire and positive, that is, $X_j \in \mathbb{N}$.

The investment alternatives, $j = 1, 2... J$, represent the different options available to upgrade the public lighting system. Among the alternatives, the following are considered:
– Replace discharge lights with LED streetlights.
– Install hybrid streetlights, which incorporate a photovoltaic panel or a micro-wind microturbine in conjunction with a battery.
– Implement controllers and sensors that allow individual management of each streetlight, dimming its light flow according to the vehicle flow.

As will be explained earlier, the energy-saving given by the implementation of each technological alternative based on the type of streetlight $A_{j,l}$ is the difference between the current energy consumption E_l and the energy consumption expected by the implementation of the technological alternative $E^*_{j,l}$.

$$A_{j,l} = E_l - E^*_{j,l} \tag{1}$$

Considering the above, the objective function to maximize the energy savings, taking into account all available upgrading alternatives, is provided below:

$$\text{FO} = \text{Max} \sum_{j=1}^{J-1} \sum_{t=1}^{T} X_{j,l,t} \, A_{j,l,t} \tag{2}$$

It should be noted that equation (2) is subjected to two constraints. First, there are a number of actions applied to the system and the available streetlights according to type and period after executing the actions. All alternatives j are considered for this constraint, as expressed in (3) below.

$$\sum_{j=1}^{J} X_{j,l,t} = LD_{l,t} \qquad (3)$$

As shown in (3), $LD_{l,t}$, depends directly on whether (or not) to implement an upgrade action in the previous period. It is also important to note that no implementation of an upgrade action represents the last alternative $j = J$. For this reason, this alternative is not considered in the calculation to determine the number of streetlights that are available after each optimization time. Then, $LD_{l,t}$ is calculated as follows:

$$LD_{l,t} = N_l - \sum_{j=1}^{J-1} X_{j,l,(t-1)} \qquad (4)$$

The second constraint in the MILP of the model is the sum of the number of upgrading actions implemented, $CI_{j,l}$, multiplied by their unitary cost. Such a sum must be lower or equal to the total budget for the evaluated period PT_t.

$$\sum_{j=1}^{J} CI_{j,l} X_{j,l,t} \leq PT_t \qquad (5)$$

In (5), PT_t depends on three components, as shown in equation (6). The first represents the available initial annual budget, PI_t. The second corresponds to the budget amount not executed from the previous period, which is added to the budget of the following period. The third term is associated with the savings obtained by improving the system's energy efficiency and the economic benefit of energy saving in the previous period. It is essential to know that including this item in the PT_t value entirely depends on the vision of the public lighting system administrator. In this article, we assume that the administrator reinvests the savings in actions to improve the street lighting system continuously.

$$PT_t = PI_t + \left(PT_{(t-1)} - \sum_{j=1}^{J} CI_{j,l} X_{j,l,(t-1)} \right) + \left(\sum_{j=1}^{J-1} X_{j,l,t} A_{j,l} CE \right) \qquad (6)$$

3 Methodological proposal

The scheme of the methodology developed to plan investments in street lighting systems was developed (see Fig. 1). As shown in the scheme, the performance criteria are defined first to determine the optimal investment alternative to be selected. The available technological alternatives for investment, J, needs to comply with the existing lighting design, which is given by the types of streetlights, l, currently installed. Then, the implementation of an alternative, j, to replace a type of streetlight, l, must maintain the photometry and luminous flux. It is also observed that each alternative, j, corresponds to a brand of streetlight, which can also include distributed generation technologies (solar and/or wind) and battery energy storage to reduce the energy consumption from the network. Additionally, the cost of implementation by alternative and type of streetlight, $CI_{j,l}$, refers to the total cost of installing and functioning streetlights.

With the data of the rated power for each alternative, j, on each type of streetlight, l, the expected energy savings, $A_{j,l}$, are calculated based on the difference between the current energy consumption and the energy consumption given by the implementation of each alternative. The energy-saving, $A_{j,l}$, the cost of implementation, $CI_{j,l}$, and the initial budget, PI_t, for each period t, are the input data that feed the optimization model.

Second, a diagnosis of the current state of the street lighting system is carried out. For this purpose, each of the existing streetlights is classified according to its technology, rated power (W), luminous flux (lm), photometry (cd), and energy consumption (kWh/year).

Finally, the MILP is responsible for evaluating investment alternatives considering a multi-period analysis. In [12–14], MILP is a powerful and flexible tool leveraged in the analysis and optimization of sophisticated and complex problems, typically in firms that deal with extremely large data sets. In this article, we considered four years. The result of the optimization model is a list that indicates a set of optimal investment actions for each period, which maximizes the energy efficiency of the street lighting system, making the best use of the available budget.

4 Case study

The proposed methodology can be applied to a real case corresponding to a street lighting system in Colombia. The technology to be replaced in the system is based on high-pressure sodium streetlights (HPS), as shown in Table 1.

For the analysis, eight decision alternatives were considered. The first six technological investment alternatives, $j = 1, 2,..., 6$, represent a change of technology from HPS to LED technology provided by different manufacturers (brands). This is due to the availability of a variety of prices and technical features in the market. The variety changes the energy efficiency depending on the manufacturer.

Alternative $j = 7$ represents the installation of hybrid solar lighting. Finally, alternative $j = 8$ is reserved for the action of not investing.

It was observed that the public lighting system is turned on utilizing photo-controls installed in each streetlight to determine the energy saving of each alternative. The average use of each streetlight approaches 13 h per day. With this data, the current energy
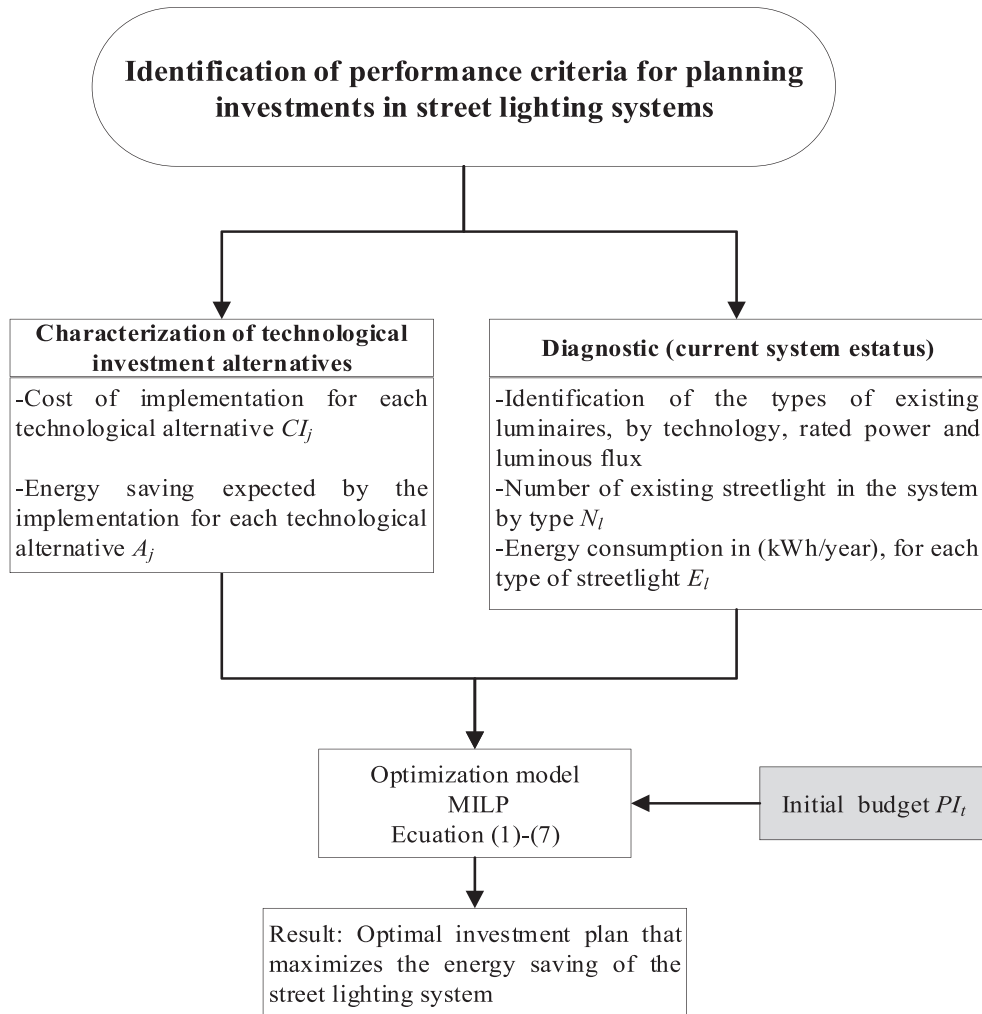
Fig. 1. Scheme of the proposed methodology for the long-term planning of the street lighting system.

Table 1. Diagnosis of the current state of the street lighting system.

Current state					
Type of streetlight	l_1	l_2	l_3	l_4	l_5
Technology	HPS	HPS	HPS	HPS	HPS
Rated power (W)	400	250	150	100	70
Efficiency (lm/W)	128	105	90	82	65
Number of streetlights	11	157	479	93	1617

consumption of the system was obtained; it equals $E_l = 1.22$ GWh/year. From this value and based on the alternatives, j, type of streetlight, l, the energy savings, $A_{j,l}$, perceived by making a one-by-one change for more efficient streetlights are calculated and reported in the table below (see Tab. 2).

Additionally, each alternative j has an associated implementation cost, $CI_{j,l}$, reported in the table below (see Tab. 3).

Four evaluation scenarios were realized, in which the combination of the variation in the cost of energy and the initial budget was considered for a planning period of four

years. Regarding the cost of energy, CE, 0.17 USD/kWh, and 0.46 USD/ kWh were considered, which correspond to the cost of electric power service in an interconnected area, such as Bogotá [17], and an isolated area [18], respectively.

Regarding the initial budget for each period, PI_t, two values were set, 160.000 USD (corresponding to 9.54% of the capital required to modernize the public lighting system and have it evaluated fully) and 320.000 USD annually (assuming an intensive investment policy). Then, the first three scenarios were optimized with the proposed MILP model, maximizing energy savings. At the same

Table 2. Energy saving in kWh/year, given by the alternative technological implementation.

	LED j_1	LED j_2	LED j_3	LED j_4	LED j_5	LED j_6	LED+PV j_7
l_1	1.145	1.153	1.1445	1.1434	1.1382	1.1518	2.2464
l_2	618.3	645.28	563.28	610.46	637.98	650.33	1404
l_3	272.2	283.61	331.96	277.99	281.64	266.76	842.4
l_4	197.1	255.86	307.20	215.32	254.29	242.61	561.6
l_5	194	204.93	219.02	167.13	200.49	183.64	393.12

Table 3. Cost of implementation, in USD, for each technological alternative.

	LED j_1	LED j_2	LED j_3	LED j_4	LED j_5	LED j_6	LED+PV j_7
l_1	1.253	1.129	1.187	1.362	1.245	1.136	5.966
l_2	1.097	925	873	1.023	967	878	4.389
l_3	853	838	820	997	886	810	3.714
l_4	746	659	786	925	749	782	2.985
l_5	667	656	740	873	721	762	2.042

Table 4. Investment plan for the four scenarios evaluated per period.

		j_2,l_1	j_2,l_4	j_2,l_5	j_3,l_3	j_3,l_4	j_3,l_5	J_6,l_2	j_7,l_5
	t_1	11	0	0	10	2	0	157	0
	t_2	0	1	0	219	0	0	0	0
ESC1	t_3	0	0	0	235	0	0	0	0
	t_4	0	0	186	15	90	1	0	0
	Total	11	1	186	479	92	1	157	0
	t_1	11	0	0	207	0	0	0	0
	t_2	0	0	83	272	93	1	0	0
ESC2	t_3	0	0	568	0	0	2	0	0
	t_4	0	0	601	0	0	0	157	0
	Total	11	0	1.252	479	93	3	157	0
	t_1	11	0	0	207	0	0	0	0
	t_2	0	0	163	272	93	2	0	0
ESC3	t_3	0	0	720	0	0	3	0	0
	t_4	0	0	3	0	0	723	157	3
	Total	11	0	886	479	93	728	157	3
	t_1	0	0	487	0	0	0	0	0
	t_2	0	0	514	0	0	0	0	0
ESC4	t_3	0	0	541	0	0	0	0	0
	t_4	0	93	75	321	0	0	0	0
	Total	0	93	1.617	321	0	0	0	0

time, the fourth scenario was performed intuitively—without optimizing—taking as a decision criterion to make the most streetlight changes in the shortest time possible and selecting the most economical alternatives. In summary, the scenarios evaluated are:

5 Analysis of results

The analysis presented in this section is based on the results reported in Tables 4 and 5 and Figure 2 above. The first three scenarios were obtained from the MILP optimization

Table 5. Expected results from the implementation of investments are provided in Table 4.

		CTI [USD]	A [GWh]	PT* [USD]	%N
ESC1	t_1	160.000	0.12	160.000	8%
	t_2	180.150	0.19	180.180	9%
	t_3	192.610	0.27	192.620	10%
	t_4	205.840	0.34	205.860	12%
	Total	738.600	0.92	738.660	39%
ESC2	t_1	319.890	0.18	320.000	9%
	t_2	351.250	0.32	351.310	19%
	t_3	374.170	0.44	374.380	24%
	t_4	394.340	0.56	394.410	32%
	Total	1.439.650	1.50	1.440.100	85%
ESC3	t_1	319.890	0.18	320.000	9%
	t_2	404.490	0.34	404.520	22%
	t_3	474.640	0.48	474.690	31%
	t_4	542.860	0.64	542.880	38%
	Total	1.741.880	1.64	1.742.090	100%
ESC4	t_1	319.539	0.10	320.000	21%
	t_2	337.254	0.21	337.428	22%
	t_3	354.969	0.32	355.047	23%
	t_4	373.565	0.46	373.797	21%
	Total	1.385.327	1.09	1.386.272	86%

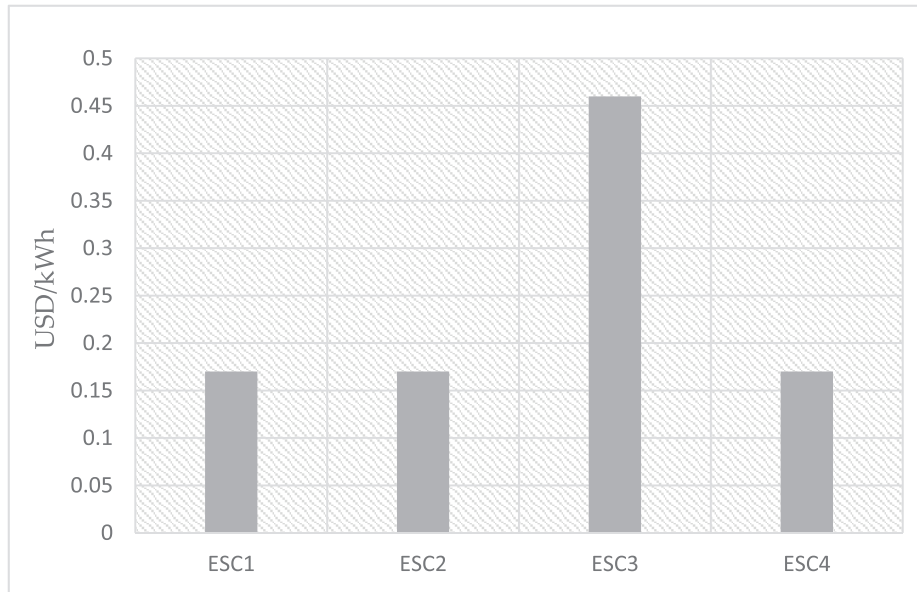* PT is calculated by using (7).

Fig. 2. The cost of energy.

model applied to the multi-period planning of investments in the lighting system. The MILP was solved using the GAMS software. The fourth scenario computation was done to acquire the most considerable quantity of luminaries of the most economical brand, using the total budget available at each period. Table 4 shows the investment plan for the four scenarios evaluated for each period. In addition, the table reports the total energy savings, the total capital investment for the modernization of the streetlights, CTI, and the percentage of streetlights changed in the system during the four simulated years.

When comparing the ESC1 and ESC2, same energy cost but different budgets, there is a notable increase in the change of streetlights of type l_5 and brand j_2 motivated by
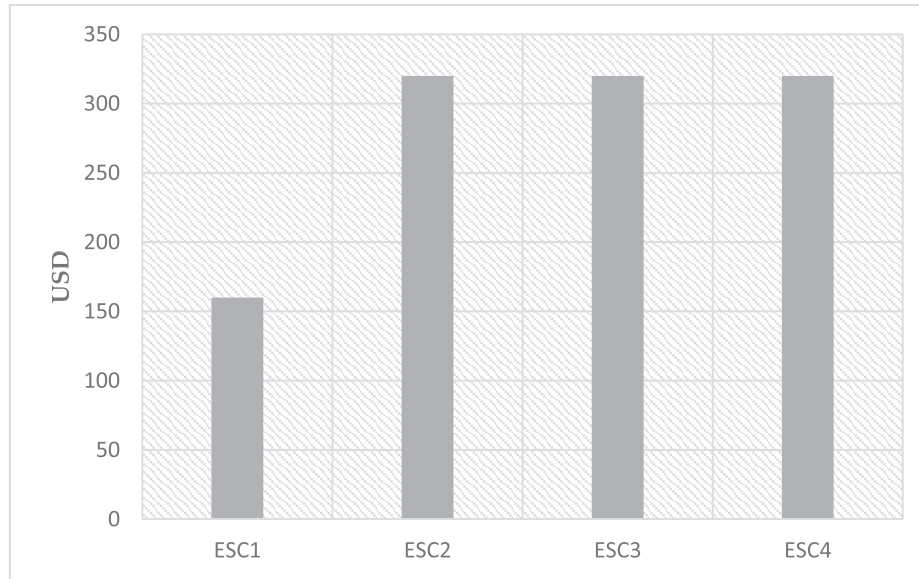
Fig. 3. The initial budget for each period. Note that for ESC1, ESC2, and ESC3, the cost is optimized, but for ESC4 it is business as usual.

the greater availability of budget in ESC2. This leads to increased energy savings and streetlight replacement percentage in the managed fleet, from 39% in ESC1 to 85% in ESC2.

From the comparison of ESC2 and ESC3, different energy costs, and the same budget, there is an increase in the total capital invested *CTI*, which equals USD 302.230. Such an increase results from the greater incentive for energy savings given by the higher energy cost for ESC3. The ESC3 is the only one that led to 100% replacement of the streetlights (2357 units). In addition, it included adoption of streetlights with photovoltaic generation capacity to reduce the distribution network's electricity demand (see Figure 3).

From the comparison between ESC2 and ESC4—an optimized scenario versus a business-as-usual scenario—the importance of performing the optimization process is noticeable because, under the same budget and energy cost, a much more significant saving is achieved for ESC2. That is, 0.41 GWh was saved in ESC2 with respect to ESC4. Although the optimized ESC2 recommends changing 1% fewer streetlights than the ESC4, greater energy savings imply a better investment plan (see Figure 4).

Finally, from the MILP optimization model, the initial budget required to change the totality of the streetlight fleet in the four years was computed. For this purpose, the two energy cost values were considered: 0.17 USD/kWh and 0.46 USD/kWh. As a result, initial budgets of USD 374.530 and USD 307.000 were obtained, respectively. This implies that for a case where the cost of energy is USD 0.17/kWh, an annual budget of USD 374.530 is required to achieve the replacement of 100 streetlights. In the case of USD 0.46/kWh, a budget of less than USD 307.000 is required since the economic recovery for energy savings is higher, thus making possible significant capital investments in streetlights.
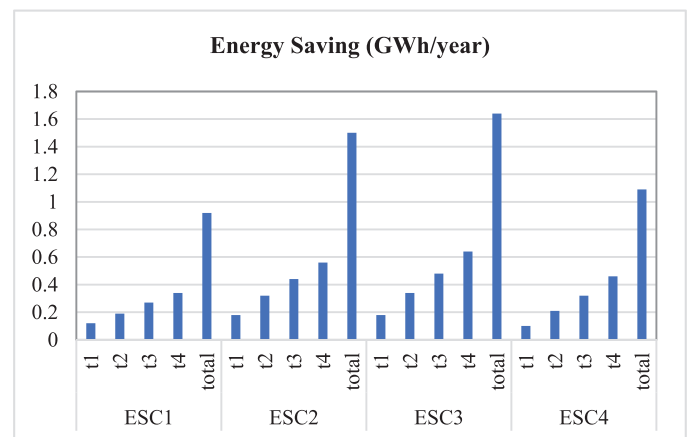

Fig. 4. Obtained energy savings for the assessed scenarios.

6 Conclusions

To our knowledge, this is the first study proposing the application of MILP in performing multi-period investment planning to upgrade streetlights. As evident from our analysis of the results, the method allows experts to devise optimal choices when making decisions involving multivariable street lighting systems, thus achieving greater energy savings. The resulting capital—from the saved energy—can be reinvested to accelerate the replacement of inefficient lights. Therefore, using MILP optimization allows leveraging of resources in streetlight systems and gears decision-makers to move towards increasing energy efficiency. Consequently, this helps in mitigating any potential impact on the environment.

From the analyses we carried out, it was observed that the cost of electric energy plays a fundamental role in planning the street lighting system; this parameter drives or breaks an alternative based on energy efficiency and implementation cost. The higher the cost of energy, the faster the adoption of alternatives to save energy, like in the case of luminaries with distributed generation systems.

It is also important to note that in state-of-the-art, no reported research has comprehensively analyzed other aspects of the existing streetlight systems. Therefore, future research be conducted to include these aspects in the design of investment plans. Moreover, future research can investigate how integrating MILP along Multi-Attribute Value theory and decision analysis can impact decision-making when conducting multi-period investment planning to enhance energy efficiency of street lighting systems.

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