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PIECEWISE TECHNO-ECONOMIC ANALYSIS OF LED CORN BULBS FOR STREET LIGHTING

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Abstract:
LED Corn bulbs are a simple solution to increase the energy efficiency of existing street lighting because their installation does not require the replacement of existing lamps. The paper analyses the techno-economic characteristics of LED Corn bulbs that can be used as a replacement for existing inefficient bulbs. Based on the collected data of more than 80 models of LED Corn bulbs, which are available on the European market, the functional dependences of power = f (luminous flux) and price = f (power) of these bulbs were determined using piecewise regression. Besides, based on the obtained functional dependencies, the effects of improving the energy efficiency of street lighting by replacing the existing High Pressure Sodium and High Pressure Mercury light bulbs with LED Corn bulbs in one city in Serbia were analysed.

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LED corn bulbs, street lighting, energy efficiency,techno-econmic analysis, piecewise regresion

1. INTRODUCTION

Public lighting is one of the key services provided by public local and municipal authorities. It can require significant amounts of electricity, which is mainly related to the use of inefficient equipment and poor management [1-3]. Public lighting includes urban and street lighting. Street lighting is also one of the most energy-intensive types of public lighting [4], which contributes to the safe use of roads [5,6].

The following light sources are predominantly used for public lighting:

1. Incandescent Light bulbs (IL) (were faced out and replaced with newer energy-efficient solutions);
2. Fluorescent lamps (FL) (more efficient than IL);
3. High PressureMercury bulbs (HPM) (more efficient than FL);
4. High Pressure Sodium bulbs (HPS) (more efficient than HPM);
5. Low Pressure Sodium bulbs (LPS) (highly efficient but used only in low-mount applications - tunnels, under bridges);
6. Metal Halide bulb (MH) (less efficient than HPS);
7. Light Emitting Diode lamps (LED) (the most efficient).

At the beginning of the 21st century, public lighting in the EU was predominantly based on HPS (48.5% share) and HPM (38.2%). Other sources included LPS - 8.6%, FL - 7.7% and MH - 2.5% [7].

To reduce the share of public lighting in total electricity consumption, the EU adopted EC Regulation No 245/2009. The regulation envisaged the progressive ban of less efficient lighting products till 2017 in the EU market - elimination of all HPM and both HPS and MH with poor value for lumen/W [8]. As an alternative to HPM bulbs, HPS bulbs were originally used, and later LED lamps. Therefore, the share of inefficient lamps decreased - in 2015, the share of HPM was 23.4%, FL 5.5% and LPS 6.1%, while the share of more efficient

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HPS increased to 53.5 % and LED to 3.8% (it is considered that the share of LED lamps before 2014 was negligible) [9].

HPM and HPS lamps are predominant in Serbia. The average share of inefficient HPM lamps in public lighting systems is around 60% [10]. HPM and HPS lamps have standardized properties and their power (*P* [W]) and luminous flux (φ [lm]) values are shown in Table 1.

Table 1: Characteristics of commonly used light sources

Type	*P* [W]	φ [lm]
HPM	125	6,200
	160	8,000
	250	12,700
	400	22,000
HPS	70	6,000
	100	8,100
	150	13,500
	250	25,200
	400	43,200

Today, LED lamps are being installed as an alternative to both HPM and HPS [11]. LED lamps are a more efficient solution that offers great opportunities for the implementation of smart systems [3,12,13]. However, due to high investment costs, several studies have shown that the implementation of LED lamps can have long payback periods [14], which is quite unfavourable for local or municipal governments. Recent research shows that the payback period can be shorter, depending on the economic and energy situation in countries [15,16].

With the advancement of LED technology, LED Corn bulbs have been developed in recent years. These light bulbs are a simple and relatively cheap solution to increase the energy efficiency of existing public lighting. They use a large arrangement of LEDs on their metal structure to allow light to propagate in the range of up to 360° similarly to HPS and HPM bulbs (Figure 1a). The other designs that have light propagation at a certain angle also exist (Figure 1b). They can also be used as an HPM or HPM replacement under appropriate conditions.

The installation of LED Corn bulbs does not require the replacement of existing luminaires which use HPM or HPS bulbs. They are installed in existing sockets; it is only necessary to bypass or remove the transformer (ballast) in the luminaire before installing the bulb.

a)

b)

Fig. 1. LED Corn bulb a) 360° light propagation, b) 180° light propagation

When installing LED corn bulbs, care should be taken that the quality of lighting they provide (according to the manufacturer's specification) satisfies or exceeds the quality of lighting which provides existing HPS or HPM light bulbs.

A comparison of the basic technical characteristics of LED Corn, HPS and HPM bulbs is shown in Table 2.

Table 2. Basic characteristics of LED Corn, HPS and HPM lamps

Type	LED Corn	HPS	HPM
Energy rating	A+	B	C
Cycling (turning on/off) [min]	Instantaneous	5-10	Up to 7
UV radiation	-	Small	Yes -requires a filter
Heat emissions	Small	15% of total energy	10-15% of total energy
Lifespan [h] (average)	35,000-50,000	18,000-24,000	15,000-24,000
Colour temperature [K]	2,700-6,500	2,700	2,700-20,000
Dimming option	Mostly No	Yes	N/A

As a relatively new technology, the LED Corn bulb for public lighting has not been much analysed in the scientific literature. The paper will analyse the techno-economic characteristics of LED Corn bulb models for street lighting available at the market. The presented analysis can help decision-makers in the planning of the projects for improving the energy efficiency of street lighting systems.

2. METHODOLOGY

The first step in determining the techno-economic characteristics of LED Corn bulbs is the collection and systematization of data on models available on the market. The paper analyses the techno-economic characteristics of more than 80 models of LED Corn bulbs, which are available on the European market. For the purposes of the analysis, only bulbs with appropriate photometric characteristics [17], level of IP protection, and an estimated lifespan of at least 35,000 h were considered.

For each of the models, data related to power - P_{corn} [W], luminous flux - φ [lm] and price - c_{corn} [€] were collected.

When determining the functional dependences $P_{corn}=f(\varphi)$ and $c_{corn}=f(P_{corn})$, it was noticed that simple linear regression does not provide satisfactory results. Therefore, a piecewise regression model was proposed to obtain more accurate dependencies. Mathematically, piecewise is defined as a function that is defined through a number of sub-functions in certain intervals, which belong to the main interval. Piecewise is a type of tool for expressing the mathematical dependencies of different parts of the main interval.

The effects of improving the energy efficiency of street lighting by replacing the existing HPS and HPM bulbs with LED corn bulbs were analyzed based on the obtained functional dependencies. The analysis was performed in one city in Serbia. It is assumed that the luminous flux of the existing system is preserved (taking into account the ageing of the bulb), in order to use the LED Corn bulbs as a replacement for existing HPM and HPS bulbs. As LED Corn bulbs emit light at an angle of 360 ° and are designed to be installed in the same luminaires as HPM/HPS bulbs, it is considered that the luminous efficacy is the same [18].

3. RESULTS AND DISCUSSION

Analysing the collected data on LED Corn bulbs, two intervals of installed power can be distinguished:

- mostly used bulbs are in lower power range – up to 150 W;
- bulbs in higher power range – above 200 W.

It can be observed that there are no models on the market in the range from 150 W to 200 W.

The functional dependence $P_{corn}=f(\varphi)$ is represented in Figure 2. The Piecewise regression model is presented using the following equations:

- for φ<21000 lm:

$$P_{corn} = 0.0075 \cdot \varphi + 0.6296 \tag{1}$$

- for φ>21000 lm:

$$P_{corn} = 4 \cdot 10^{-7} \cdot \varphi^2 - 0.019 \cdot \varphi + 416.4 \tag{2}$$

The linear function best fits for luminous flux up to 21000 lm and installed power up to 150 W. On the other side, the quadratic function best describes the dependence of luminous flux in the range 21000 - 40000 lm and installed power above 200 W.

It can be concluded from the equation that 7.5 W of light-emitting diodes should be installed to achieve an additional 1000 lm of lighting, for light bulbs with an installed power of up to 150 W. Practically, this value can be taken for the entire range of solutions.

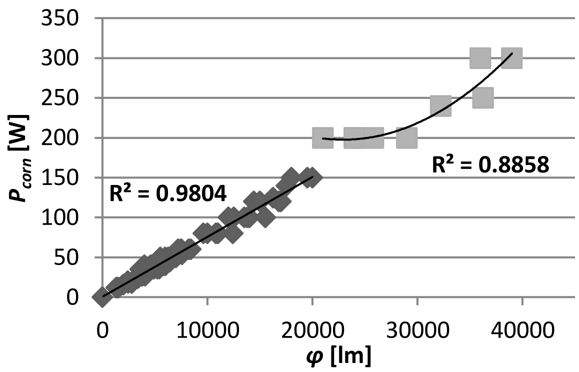

Fig. 2. Power as the function of luminous flux for available LED corn bulbs (data from [17])

Based on the collected data on available models of LED Corn bulbs and their prices, the dependence of the price of these bulbs on installed power was also obtained, Figure 3. The functional dependence $c_{corn}=f(P_{corn})$ was also defined using the piecewise method. A clear differentiation can be made between low-cost models and higher price range models. The analysis concluded that the models in the higher price range belongs to reputable manufacturers with a guaranteed lifespan of up to 50,000 hours.

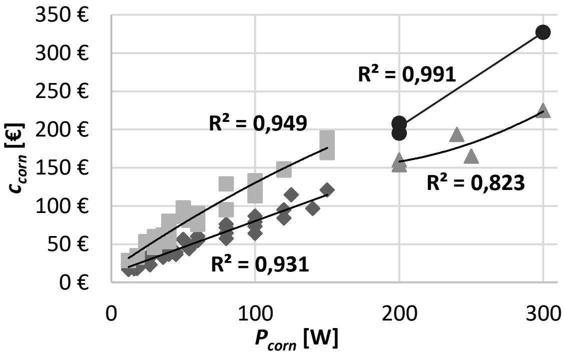

Fig. 3. The price of LED corn bulbs as a function of installed power (data from [17])

3.1 Potential annual energy savings

The principle of replacement, which implies the preservation of luminous flux, must take into account the effect of changes in luminous flux due to ageing. The impact of ageing was estimated based on the manufacturer's analysis.

The calculated power of LED Corn bulbs that are required for the replacement of existing HPM bulbs are shown in Table 3, whilst LED Corn alternatives for HPS bulbs are shown in Table 4.

Table 3. Equivalent power of LED Corn alternative for HPM

HPM [W]	φ [lm]	LED corn [W]
125	6200	51
160	8000	64
250	12700	98
400	22000	165

Table 4. Equivalent power of LED Corn alternative for HPS

HPS [W]	φ [lm]	LED corn [W]
70	6000	49
100	8100	64
150	13500	103
250	25200	188
400	43200	315[1]

The power of alternative LED Corn bulbs is significantly less than that of existing HPM and HPS bulbs. This results in lower energy consumption for the same time engagement. The planned annual engagement of public lighting is conditioned by the length of the day, i.e. the night, depending on the specific location.

The analyses of potential annual energy savings and related economic effects are presented for the example of the city of Kragujevac (44°0’51” N, 20°54’42” E). According to the annual plan, the number of working hours of public lighting in Kragujevac is τ = 4,070 h. A total number of 16,441 HPM bulbs and 7,307 HPS bulbs have been installed in the city. Each of the existing HPM luminaires annually consumes from 559.63 kWh to 1,790.8 kWh of electricity, while each of HPS luminaires consumes from 313.39 kWh to 1,790.8 kWh during the same period (Table 5) [10].

Table 5. Annual electricity consumption of existing HPM and HPS luminaires in the City of Kragujevac

Luminaires	Power [W]	Consumption [kWh/a]
HPM	125	559.63
HPM	160	716.32
HPM	250	1,119.25
HPM	400	1,790.80
HPS	70	313.39
HPS	100	447.70
HPS	150	671.55
HPS	250	1,119.25
HPS	400	1,790.80

Annual energy savings ΔE [kWh/a] and annual CO_2 reduction [kg/a] that would be achieved using LED Corn bulbs as an alternative to HPM and HPS bulbs are shown in Figures 4 and 5. For the calculation of CO2 reduction, the annual carbon emission factor for electricity generation and distribution network in Serbia of f_{CO2}=0.8 kg/kWh was taken into account considering the current way of producing electricity (roughly 2/3 from lignite, 1/3 from hydropower) [19].

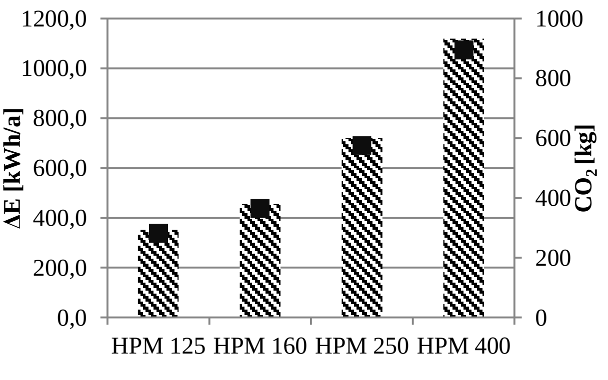

Fig. 4. Energy savings and CO_2 emission reductions as the results of HPM replacement

1 Only LED corn bulbs up to 300 W are available on the market today.

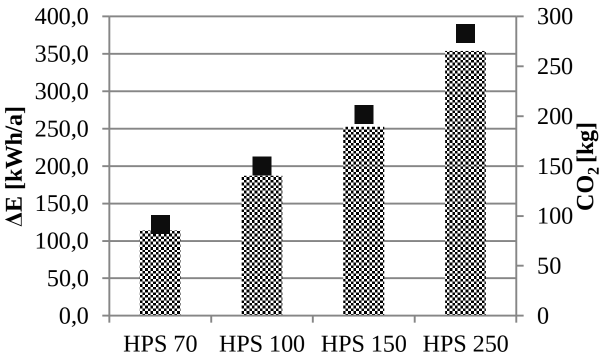

Fig. 5. Energy savings and CO_2 emission reductions as the results of HPS replacement

The savings of electricity are proportional to the power of the existing bulbs, so greater savings are achieved for higher bulb power.

The prices and costs that are used in estimating the overall costs of implementing certain measures have been obtained by the analysis of the artificial lighting market. Table 6 shows the average prices of HPM and HPS bulbs for street lighting that can be found in the local market.

Table 6. Average prices of HPM and HPS bulbs

Type	P(W)	Price of a single bulb [€]
HPM	125	2.90
	160	3.75
	250	5.48
	400	8.03
HPS	70	6.63
	100	8.42
	150	9.53
	250	11.60

The cost of a single bulb replacement (8 €) can be considered the same for all types, except for LED Corn (12€) because it includes ballast bypassing. The maintenance costs for LED corn bulbs are lower since their lifespan is considerably bigger.

Considering the fixed price of electricity in the public lighting system (0.062 €/kWh), the obtained annual financial savings are proportional to the achieved electricity savings (Tables 7 and 8) [20].

Table 7. Financial savings as a result of HPM replacement with LED corn

	HPM 125	HPM 160	HPM 250	HPM 400
Saving [€/a]	22.00	28.49	45.02	69.95

Table 8. Financial savings as a result of HPS replacement with LED corn

	HPS 70	HPS 100	HPS 150	HPS 250
Saving [€/a]	7.12	11.70	15.77	22.13

The use of LED Corn bulbs to improve the energy efficiency of public lighting systems has positive economic effects. The economic effects depend on the installed power of light sources and available models on the market (Figures 6 and 7). The installation of LED corn bulbs provides a short payback period for low-cost models ranging from 1.5 years to replace the HPM 250 W to 1.7 years to replace the HPM 125 W. On the other side, payback periods in the case of models from a higher price range, are from 2.06 to 2.81 years.

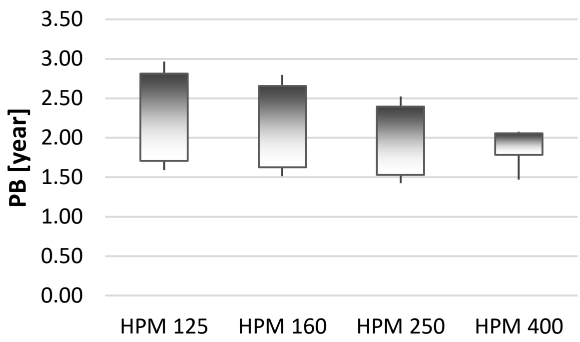

Fig. 6. The payback period for replacing existing HPM bulbs

As with the replacement of existing HPM, the replacement of existing HPS with LED corn bulbs is a cost-effective solution. In this case, the payback periods are slightly longer. The payback period for low-cost models ranges from 2.67 to 3.29 years, while for the models at the higher price, the range is from 4.37 to 5.1 years.

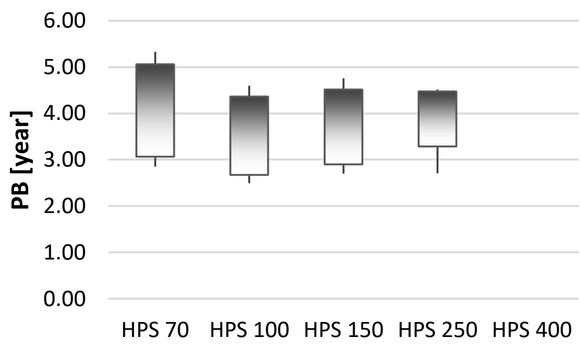

Fig. 7. The payback period for replacing existing HPM bulbs

4. CONCLUSION

Obtained functional dependencies can be used when planning energy efficiency programs and projects, i.e. assessing the effects of implemented measures. The application of the conducted analysis and defined dependencies are shown in the example of improving the energy efficiency of street lighting by replacing the existing HPS and HPM bulbs with LED corn bulbs in one city in Serbia.

Energy savings and associated CO_2 emission reductions increase with the increase of power of existing bulbs. Replacing a single HPM bulb with an LED corn equivalent can yield up to 1100 kWh/a of electricity saving. In the case of HPS replacements, the saving could be up to 300 kWh/a. Associated CO_2 reduction amounts up to 900 kg when replacing HPM, i.e. up to 280 kg for HPS replacement.

Even in the case of relatively low electricity prices, such as in Serbia, the replacement of HPM with LED corn bulbs is a satisfactory solution for the whole source power range. Although, it must not be forgotten that LED corn bulbs should be installed only at properly functioning existing luminaires. LED corn bulbs should not be installed in an existing outdated or poorly maintained luminary. In such a case, the new efficient luminary must be installed as a replacement.

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