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The system of indicators of street lighting systems energy efficiency

To cite this article: K R Valiullin 2020 *IOP Conf. Ser.: Mater. Sci. Eng.* **791** 012048

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The system of indicators of street lighting systems energy efficiency

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Abstract. One of the important tasks that arise when choosing a project for the modernization of any electric power system is estimation of its energy efficiency. Criterion of energy efficiency is one of the most important for development plans of electrical systems, as well as other criterions. Evaluation of energy efficiency of street lighting systems is complex task, because it should take in account effectivity of street lighting that cannot be directly measured. This paper propose a system of indicators of street lighting systems, based on process of energy transformation and requirements of regulatory documents. Suggested indicators rate every elements of street lighting systems from electrical grid to luminaires, and can be used for estimation of energy efficiency of existing street lighting systems or selection of the most energy efficient option of electrical street lighting system modernization. Proposed indicators can be also used for determination of the most effective geometrical position of luminaire and can be used for energy efficiency optimization of street lighting systems on the design stage.

1. Introduction

At present, the government of the Russian Federation has marked a trend to increase the energy efficiency of electrical systems, to reduce their energy consumption with remained or increased useful effect. So, the criterion of energy efficiency is one of the most important for development plans of electrical systems, as well as reliability, economic and ecological criterions. Assessment of energy efficiency allows you to choose the most optimal option of energy system development. At the macro economy level good results show methods of energy saving projects evaluation, based on Data Environment Analysis [1-3]. For electrical systems and appliances, the evaluation of energy efficiency is a complex task, because this indicator takes into account not only the amount of energy consumed to create a useful effect, but also the useful effect itself, which in many cases cannot be directly quantified. There are researches dedicated to estimation of energy efficiency on the different levels from large plants [4] and pumping stations [5] to particular induction motors [6].

Street lighting systems (SLS) are the one of the most important parts of city energy system [7]. Nowadays in many cities SLS are being upgraded: usually modernization projects include replacement of old mercury or sodium vapor lamps to LED or implementation of modern lighting control systems. As a rule there are several modernization projects and choice of one of them is performed by economic criterions [8]. But cheapest project usually is not the best choice, so there is a necessity of development of additional criterions for choice of the best SLS modernization option. One of this criterions could be the energy efficiency criterion.
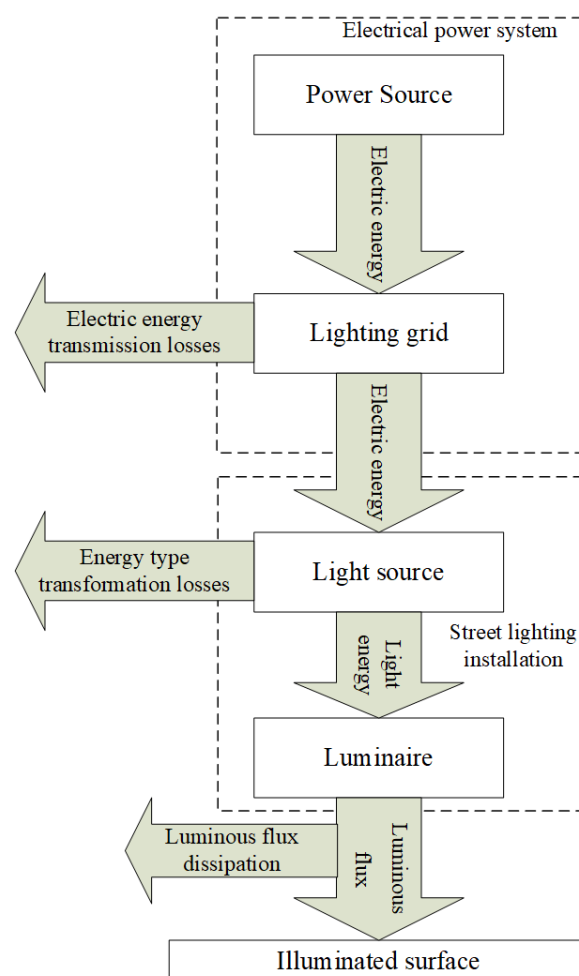
Energy efficiency of electrical system is usually estimated as ratio of useful effect to energy consumption of this system. Energy consumption of SLS can be easily calculated, but useful effect of SLS is safety and comfort of citizens, that cannot be directly measured. For this reason, development of energy efficiency indicators for street lighting systems is actual problem.

GOST 54993-2012 that declares energy efficiency indicators and classes can be applied only for household light sources with luminous flux no more than 6500 lm. Because the most of street lighting installations have luminous flux much more than 6500 lm, this standard cannot be used for estimation of their energy efficiency. In accordance with Code of rules SP 52.13330.2016 "Daylighting and artificial lighting", energy efficiency of street lighting (SLI) is evaluated by the indicator of the SLI relative power density, which is insufficient to estimate the energy efficiency of the entire SLS, because it consists of several components: power source, lighting networks, street lighting installations.

There are several studies of foreign scientists dedicated to problems of energy efficiency estimation of street lighting systems [9-15], that suggest indicators, based on energy consumption, economical values and street illuminance, but proposed indicators estimate energy efficiency of street lighting installations but not of entire SLS. And it is also worth noting that there is no researches made in accordance with Russian Federation street lighting standards.

2. Proposed methods of street lighting systems energy efficiency evaluation

For development a system of indicators that estimates the energy efficiency of each SLS component, consider the process of energy transfer between SLS elements, Figure 1.

Figure 1. Energy transformation in street lighting system.

2.1. Evaluation of energy efficiency of electrical power systems

Transmission of electrical energy from the power source to the SLI in the power lines is accompanied by energy losses that depend on the flowing current, resistance of the conductors and length of the supply lines. Energy losses in the power supply system can be estimated through the value of its conductor's resistance and the voltage drop from the nominal value in the most distant point:

$$\Delta W = \frac{(U - U_0) \cdot Z}{Z^2} = \frac{\Delta U^2}{Z},$$

(1)

where U – voltage at the most remote from energy source lighting installation, V;
U_0 – energy source voltage, V;
Z – full resistance of power transmission line, Ω.

Resistance of the power lines cannot be used as a reliable indicator of energy efficiency, because in such case short line will be always more energy efficient that is incorrect. So, it is suggested to evaluate the efficiency of electric power transmission from the power source to the SLI through the amount of the voltage drop at the most remote from energy source lighting installation:

$$\Delta U = \frac{U - U_{rated}}{U_{rated}} \cdot 100\%,$$

(2)

where U – voltage at the most distant lighting installation, V;
U_{rated} – rated voltage of the network, V.

The higher value will correspond to the greater value of the loss and lesser value of energy efficiency. It should be noted that the demands to voltage drop are declared in regulatory documents. According to them, the voltage loss in these networks should not exceed 5% for the most remote SLI.

2.2. Luminous efficacy indicator

Conversion of electric energy into light energy in SLI, can be characterized by well-known indicator of luminous efficacy:

$$\eta = \frac{\Phi}{P},$$

(3)

where Φ – light flux emitted by the light source, lm;
P – power consumption of the SLI, W.

Luminous efficacy indicator characterizes the efficiency of conversion of electrical energy into light energy in a SLI. A higher value of the indicator corresponds to a higher energy efficiency. For fluorescent lamps the value of this indicator lies in the range of 78-115 lm/W, for LED - 90-150 lm/W [10].

2.3. Street lighting installation relative power density indicator

In the Code of rules SP 52.13330.2016 proposed the value of SLI relative power density which is an integral value linking electrical and lighting characteristics of SLI. The indicator of SLI relative power density is measured in mW/m^2·lx determined by the formula:

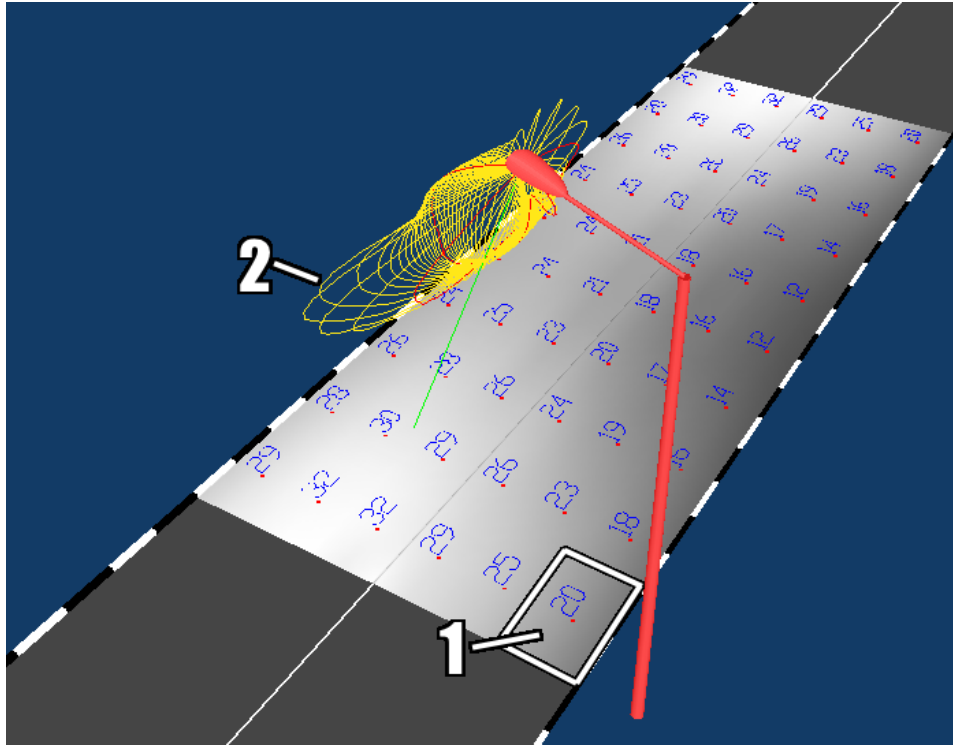$$D_p = \frac{P}{\sum\limits_{i=1}^{n} E_i \cdot S_i},$$

(4)

where P – total rated power of SLI in the area, W;
E_i – illuminance of a single section of the area, W;
S_i – the area of a single section of the considered area, m^2.
n – number of sections in the area.

For evaluation of this indicator, illuminated area should be divided into sections with area S_i with calculated mean value of illuminance E_i (Figure 2).

Figure 2. Illustration for relative power density indicator evaluation. 1 – single section and its mean illuminance; 2 – luminous flux distribution.

Bigger values of indicator correspond to lower energy efficiency. The maximum allowable values of the indicator are presented in Code of rules SP 52.13330.2016 and depend on the class of the illuminated street.

2.4. Indicator of efficiency of transmission of a light flux from street lighting installation to an illuminated surface (Luminous flux transmission coefficient)
The illuminance of the surface is measured in lux. One lux is illuminance (E) of the surface, with an area (S) of 1 square meter, when a light flux (Φ) of 1 lumen falls on it. From this definition, it is possible to find the light flux that falls on the considered area:

$$\Phi = E \cdot S, \tag{5}$$

Part of the light flux generated by the SLI dissipates in the environment, so it is proposed to introduce an indicator that takes into account the efficiency of the transmission of the light flux from the SLI to the illuminated surface. The value of the indicator can be determined by the formula:

$$\eta_{tr} = \frac{\sum_{i=1}^{n} E_i \cdot S_i}{\Phi_0}, \tag{6}$$

where Φ_0 is the luminous flux produced by the SLI, lm.

Luminous flux transmission coefficient is a relative dimensionless value equal to the ratio of the light flux that reached the surface to the light flux created by the SLI. For an ideal SLI, η_{tr}=1, that means, that all luminous flux, created by light source reach illuminated surface.

2.5. The indicator of the efficiency of the distribution of the light flux over the illuminated area (coefficient of regulatory compliance of the light flux)

It is difficult to obtain a qualitative estimate of the distribution of the light flux over the area, so in the work suggested evaluation approach based on the quantitative indicators given by the illumination standards. For an ideal SLS, the illumination at all points of the illuminated area will be equal to given in normative documents. Up upwards deviations indicate a possible decrease in the luminous flux, and hence the power of the lighting installations, and the downwards deviations indicate the inefficiency of the SLS. For evaluation of the efficiency of the distribution of the luminous flux proposed the value of the coefficient of regulatory compliance of the light flux:

$$\eta_{norm} = \frac{\sum_{i=1}^{n} E_i \cdot S_i}{E_{norm} \cdot S},$$ (7)

where E_{norm} – illumination, according to the standarts and regulatory documents, lx;
S – illuminated area, m^2.

Coefficient of regulatory compliance of the light flux is a strictly positive dimensionless value. The most energy efficient SLS corresponds to the value of the indicator closest to 1. Values less than 1 indicates mismatch with the standards of street lighting. The values of the coefficient greater than 1 correspond to the situation in which the considerate surface illumination is higher than the standards. That situation indicates an overestimated light flux and the power of the SLI, which leads to lower energy efficiency.

The proposed system of indicators is presented in Table 1.

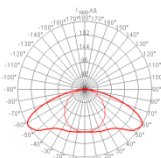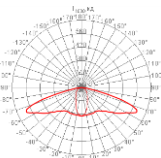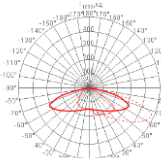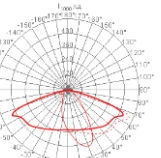**Table 1.** Proposed indicators of street lighting energy efficiency.
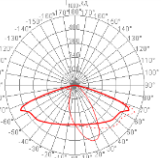
Energy efficiency indicator	Indicator meaning	Influencing SLS parameters
Lighting network voltage loss	Efficiency of electric power transmission from the power source to the SLI	- SLI power; - lighting network length; - lighting network wires cross section.
Luminous efficacy	Efficiency of conversion of electrical energy into light energy in a SLI	- energy conversion efficiency of a light source and its ballast/driver.
Luminous flux transmission coefficient	Efficiency of the transmission of the light flux from the SLI to the illuminated surface	- light intensity distribution curve; - parameters of luminaire; - geometric position of the SLI.
Coefficient of regulatory compliance of the light flux	Efficiency of the distribution of the luminous flux	- illumination standarts; - light intensity distribution curve; - parameters of luminaire; - geometric position of the SLI.
Street lighting installation relative power density	Efficiency of use of electric energy for creating illuminance on the surface	- SLI power; - light intensity distribution curve; - parameters of luminaire; - geometric position of the SLI.

3. Results

To approbate the proposed system of indicators, five street lighting projects with different types of luminaires have been calculated with use of the Light-in-Night Road software. In all projects was con-

sidered a section of a two-lane road, 150 meters long, 7.5 meters wide, belonging to class B2 (highways and streets of district importance in the city center), the average horizontal illumination should be at least 15 lx. The arrangement of the luminaires is one-side, the height of the support is 8 meters, the step between the luminaires is 20 meters. Parameters of luminaires are presented in Table 2, values of energy efficiency indicators for each of the projects are presented in Table 3.

Table 2. Parameters of luminaires for different projects.

Parameter	Number of project				
	1 (mercury lamp)	2 (sodium vapor lamp)	3 (LED)	4 (LED)	5 (LED)
Light flux, lm	13000	15000	11180	11000	9500
Rated power, W	250	150	98	120	100
Light intensity distribution curve					

Table 3. Comparision of street lighting projects with different luminaires

Indicator	Number of project				
	1 (mercury lamp)	2 (sodium vapor lamp)	3 (LED)	4 (LED)	5 (LED)
Lighting network voltage loss,%	0.89	0.53	**0.35**	0.43	0.36
Luminous efficacy, lm/W	52	100	**114**	91.67	95
Luminous flux transmission coefficient	0.17	0.29	0.207	**0.327**	**0.327**
Coefficient of regulatory compliance of the light flux	0.982	1.934	**1.031**	1.596	1.379
Street lighting installation relative power density, mW/m^2·lx	113.1	34.46	42.25	33.4	**32.22**

Proposed system of indicators makes it possible to determine which of the possible variants of the luminaires will be the most energy efficient under given conditions.

4. Discussion

Also, the proposed energy efficiency parameters were calculated for a given luminaires (luminous flux 13,000 lm, wide light intensity curve) and various variants of the geometric position of the SLI. Variation of values of energy efficiency indicators for different versions of the geometric position of the luminaries is shown in Figures 3-5.

According to Figure 3, as the distance between the SLI changes, the value of the luminous flux transmission coefficient increases, because the total illuminated area increases. However, at a certain

moment the maximum of the illuminated area is reached and the characteristic increase stops. From the point of view of this parameter, energy efficiency of different distances between luminaires exceeding 10 meters is equivalent.

A similar situation is observed when considering the change in the SLI relative power density - variants with a distance between SLI exceeding 10 meters are equivalent in their energy efficiency. In this regard, to determine the optimal distance, it is proposed to use the coefficient of regulatory compliance of the light flux - the highest energy efficiency is achieved with the value of this parameter closest to 1, which corresponds to the distance between the SLI at 19 meters.

According to Figure 4, with increase of luminaire installation height luminous flux transmission coefficient decreases, because of increasing luminous flux dissipation. Similarly decreases the coefficient of regulatory compliance of the light flux and relative power density.
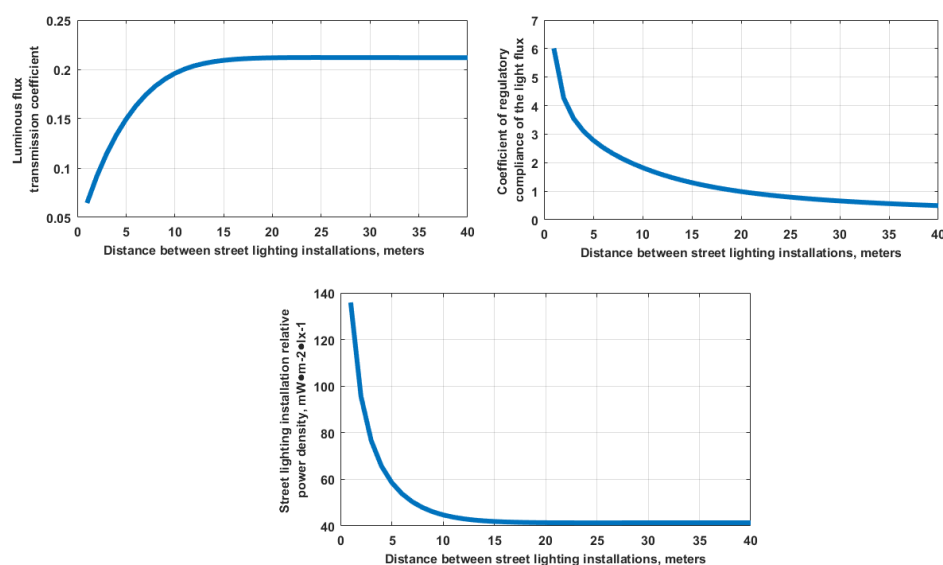
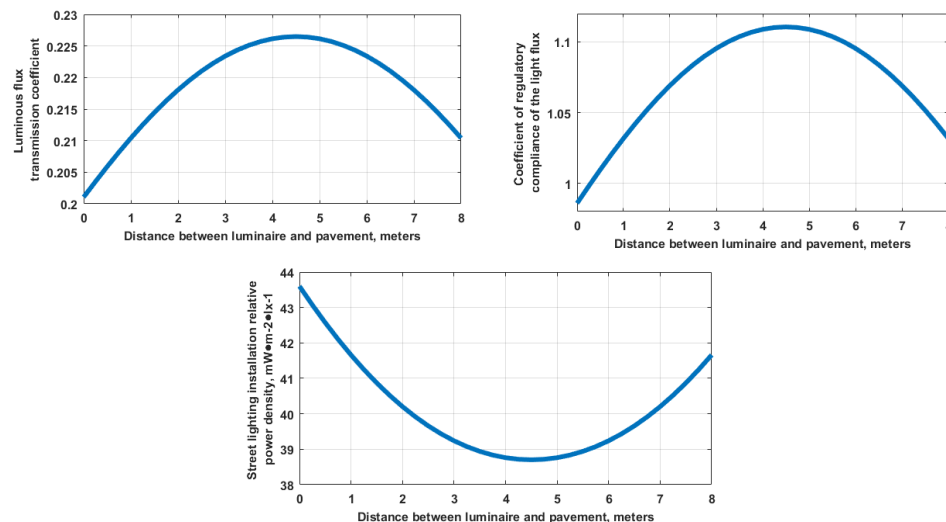**Figure 3.** Relation of energy efficiency indicators and distance between street lighting installations.
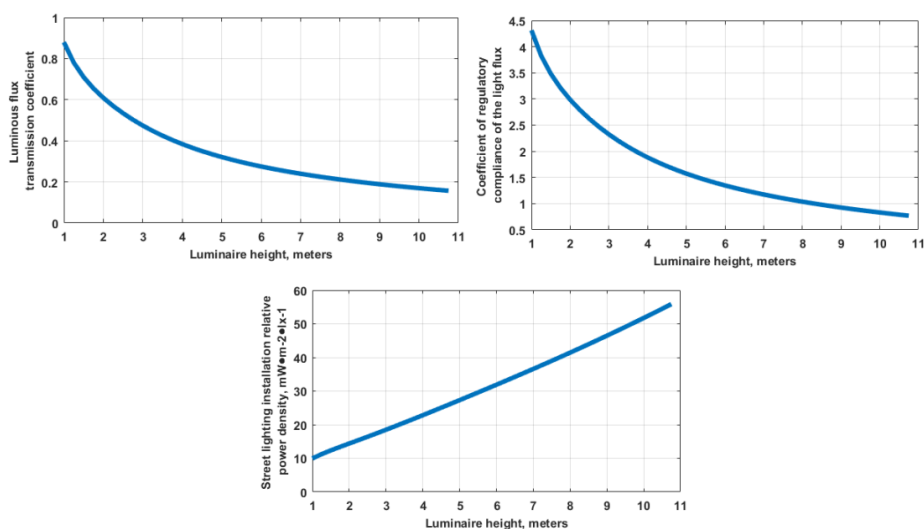
Figure 4. Relation of energy efficiency indicators and height of luminaire installation height.

Figure 5 shows relations of energy efficiency indicators and distance between luminaire and pavement. According to them can be found optimal value of 4,5 meters between luminaire and pavement.

Thus, the proposed system of indicators allows us to consider the task of increasing the energy efficiency of the SLS as a multidimensional optimization task, taking into account the boundary conditions imposed by technical and economic requirements.

Figure 5. Relation of energy efficiency indicators and distance between luminaire and pavement.

5. Conclusion

In paper was proposed a system of indicators for estimation of street lighting systems energy efficiency. Based on the consideration of the processes of energy transmission and transformation, a system of indicators estimate energy efficiency of each element of street lighting system. Voltage losses in the lighting network rate energy efficiency of electrical power system; the light output of the light sources can be used as measure of light source energy efficiency; the transmission coefficient of the light flux, the coefficient of compliance of the light flux to the standard and the relative specific power installations of street illumination estimate energy efficiency of luminaire and its geometric position. Experiments proved, that proposed system of indicators is consistent and allows to choose the most energy efficient option for the development of SLS.

Introduction of the system of indicators of energy efficiency of the SLS allows to reduce the task of increasing its energy efficiency to the problem of multicriteria optimization with known solution methods. It becomes possible to take into account economic, technical and other constraints in the form of boundary conditions for the optimization problem. Thus, the introduction of the system of criteria for the estimation of energy efficiency of the SLS can be considered as the first step towards the automation of the process of designing an energy efficient SLS.

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