UDC 620.9:628.9:502
DOI: 10.15587/1729-4061.2025.348864

ASSESSMENT OF ENERGY EFFICIENCY AND ENVIRONMENTAL PERFORMANCE OF LED LIGHT SOURCES BY THE ECODESIGN METHODS

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The object of the study is the processes and factors that determine the energy efficiency and environmental friendliness of LED light sources and contribute to reducing negative impacts on the environment and human health.

The work investigated the levels of energy efficiency and environmental friendliness of commercial samples of LED luminaires for compliance with the requirements of the EU Commission Regulations on Energy Labeling No. 2019/2015 and on Ecodesign No. 2019/2020. The network efficiency coefficient η_{TM} (lm/W) was taken as the energy efficiency criterion. The main environmental friendliness criteria: the limit level of flicker luminance P_{stLM} and the visibility of the stroboscopic effect SVM are established by the EU Commission Regulation No. 2019/2020; the limit level of blue light hazard should not exceed the risk group RG1 according to EN 62471:2018; the limit levels of the Unified Glare Rating UGR according to ISO 8995-1:2025.

LED luminaires using high-power LEDs have a η_{TM} coefficient of 135–170 lm/W and comply with energy efficiency classes D and C according to Commission Regulation EU No. 2019/2015. The η_{TM} coefficient of luminaires with low-power LEDs is 100 lm/W, energy efficiency class F.

Luminaires with low-power LEDs correspond to the RG0 risk group in terms of blue light safety, and luminaires with high-power LEDs correspond to the RG1 risk group. All tested luminaires meet the requirements of Commission Regulation EU No. 2019/2020 in terms of flicker luminance and visibility of the stroboscopic effect ($P_{stLM} < 1$, SVM < 0.4). Light exceeding the established limit values for these indicators has a negative impact on health and can be classified as light pollution.

Light sources have the greatest impact on the environment as a result of the consumption of electrical energy

Keywords: light sources, lighting systems, light sources, LED lighting systems, light pollution, environment

Received 02.10.2025
Received in revised form 11.12.2025
Accepted 19.12.2025
Published 30.12.2025

***How to Cite:** Nazarenko, V., Sorokin, V., Pekur, D., Shpak, S., Basova, I., Baghirov, S., Kozhushko, G. (2025). Assessment of energy efficiency and environmental performance of led light sources by the ecodesign methods. Eastern-European Journal of Enterprise Technologies, 6 (10 (138)), 48–59. https://doi.org/10.15587/1729-4061.2025.348864*

1. Introduction

Ecodesign is a priority area of environmental and energy conservation policy, which provides for measures to reduce energy consumption and reduce negative impacts on the environment and people at all stages of the product life cycle. It is used as a preventive method to optimize the impact of energy-consuming products on the environment. Energy-consuming products should be evaluated according to such parameters as: fuel, material and other resource consumption; emissions of harmful substances into the atmosphere; physical pollution, which is defined as noise, electromagnetic fields, optical radiation, etc.

Reuse of materials is considered a key factor for a closed-loop economy, which allows reducing resource consumption and preventing the formation of new waste streams [1]. However, when it comes to products related to electricity consumption at the use stage, the predominant role is played by CO_2 emissions generated during electricity generation [2].

In Directive 2009/125 [3], the EU established a framework for ecodesign requirements for energy-using products and common basic principles for the sale of energy-using products within the EU. The Directive also applies to electric lamps and luminaires. The new EU Regulation 2024/1781 [4] extends the framework for ecodesign requirements to improve the environmental sustainability of products and reduce their environmental and carbon footprint throughout their life cycle. They aim to improve the following aspects of products: durability; reliability; energy efficiency; resource efficiency; recyclability; waste reduction, etc.

The most common tool for determining the environmental profile of a product is LCA (Life Cycle Assessment) [5–7]. LCA is a tool for systematically assessing the potential environmental impact of a product or service during its life cycle.

The methodological basis for LCA research is the international standards ISO 14040:2006 and ISO 14044:2006. In addition, LCA has been improved by using eco-indicators of sustainability. These indicators are used as a tool for developing environmental policy. They allow comparing products and provide the necessary information for making decisions about future changes in the direction of sustainable development.

It should be noted that there are no methods for assessing the impact on the environment that take into account all factors that create pollution and affect human health. The most common impact categories used in LCA of light sources are: global warming potential caused by greenhouse gas emissions; acidification by sulfur dioxide and nitrogen oxide; toxicity caused by heavy metals, acids, etc.; resource depletion [7]. One of the disadvantages of LCA of electric light sources is that the environmental impact of the light itself is not taken into account at the use stage [7].

The International Commission on Lighting (Commission Internationale de l´Eclairage – CIE), based on the analysis of studies on the impact of light on the environment and human health, recommends in the publication CIE PS 003:2025 to avoid undesirable effects when designing lighting systems. This applies, first of all, to luminance flicker and stroboscopic effects, discomfort glare and other phenomena that qualify as light pollution. According to the definition given in CIE S 017/E:2020, light pollution is the total sum of all harmful effects of electric light. It is now generally recognized that light pollution causes a significant negative impact on the environment and is the most distorting element of nightlife [8, 9].

The requirements for light sources are constantly increasing, which is confirmed by the adoption of new directives and regulations in the EU. In 2019, the European Commission announced a new Commission Regulation (EU) 2019/2020 [10], which revised the minimum requirements for LED light sources. The Commission Regulation (EU) 2019/2020 on ecodesign [10] is complemented by the Commission Regulation (EU) 2019/2015 [11] on energy labelling, which provides information on the energy efficiency of a product. The Commission Regulation (EU) 2019/2015 sets out rules for calculating energy efficiency classes based on the overall network efficiency η_{TM} (lm/W).

The new ISO/CIE standard 8995-1:2025 sets out requirements for workplace lighting, taking into account the non-visual effects of light on humans. To achieve the recommended values for circadian light efficiency, higher levels of illuminance and light quality are required compared to the requirements for visual functions. Therefore, the study of the parameters of LED light sources for compliance with the requirements of Commission Regulation (EU) No. 2019/2020 [10] and ISO/CIE 8995-1:2025 recommendations is a relevant issue for lighting engineering.

2. Literature review and problem statement

In [7], a critical analysis of the life cycle and environmental assessment of LED lamps and their impact on the environment was conducted. It was shown that the luminous efficacy for commercial LED lamps reached the level of 80–100 lm/W. When assessing energy efficiency, the type of light source (directional or non-directional) was not taken into account, as well as the features of operation (from the power supply network or autonomous power supply). The quality of color rendering, which affects the level of energy efficiency, was also not taken into account. It is assumed that the luminous efficacy of light sources, which is defined as the ratio of luminous flux to power (lm/W), is a key parameter when assessing the environmental impact at the "life cycle (use) stage". As a disadvantage of life cycle assessment on the environment, it is noted that the impact of such parameters as the emission spectrum, flicker luminance, glare created by high luminance of LEDs, and the photobiological hazard of blue light is not taken into account. These studies were conducted before the entry into force of the EU Commission Regulation on Ecodesign No. 2019/2020 [10], which sets new requirements for the characteristics of LED sources. In work [12], non-directional LED lamps were studied for compliance with the requirements of the EU Commission Regulation [10]. It was shown that the network efficiency η_{TM} for lamps with a power of 5–12 W was from 90 to 120 lm/W (energy efficiency classes F, E). The energy efficiency of LED lamps with directional and non-directional light was not studied, so there is every reason to argue about the feasibility of conducting these studies.

Ecodesign is interpreted as "the integration of environmental aspects in product design in order to reduce adverse environmental impacts throughout the life cycle" [10]. Commission Regulation (EU) No. 2019/2020 [10] focuses on the life cycle stages that have the greatest impact on the environment. Light sources have the greatest impact during their use phase through their energy consumption. Therefore, one of the main challenges in the lighting sector is to reduce energy consumption, which is constantly increasing due to the increasing demand for lighting.

Nowadays, people are overexposed to blue light from LEDs, especially at night. Animal studies [13] show increased mortality of photoreceptors in the eye after exposure to commercial white LEDs. The effect of LED radiation on the retina has been tested in several studies under conditions close to those found in the home environment [14]. They suggested that blue light may have a negative effect on the retina not only under extreme conditions. However, these studies were conducted over a short period of time (maximum 1 month) and most of these experiments do not fully reflect the real picture [15].

The European Scientific Committee on Health, Environment and Emerging Risks (SCHEER) has issued a statement stating that there is no evidence that the photobiological hazard group is exceeded by LED light sources for general lighting above RG1. On the other hand, the cumulative effect of this exposure may lead to negative consequences in the long term. The standard on photobiological hazards of blue light EN 62471:2008 was developed based on the results of exposure to intense light and did not take into account the effects of repeated exposure. The question is whether these very low doses during systematic exposure can be harmful. Research is needed to better understand the mechanisms of photochemical damage and to determine the potential long-term effects of blue light.

In [16, 17], the results of studies on the influence of flicker on biological processes and the conditions for their occurrence are summarized. In particular, it is noted that in the frequency range of 3–70 Hz, flicker can cause seizures in people diagnosed with epilepsy, as well as some specific neurological symptoms. Less obvious biological effects occur when exposed to invisible flicker – this is eye strain, fatigue, headache.

The flickering of the luminance of LED lamps and luminaires powered by an alternating current network is not a problem of the LEDs themselves, but is associated with power supplies (drivers). Drivers, among other functions, convert alternating current into direct current. This conversion is never ideal, always creates a certain ripple in the output current, which in turn creates a modulation of the luminance of the light. Manufacturers sometimes, in order to reduce the cost of LED lamps and luminaires, use cheap low-quality drivers, so the high level of flicker is primarily a problem of cheap LED products. Another disadvantage of LED lamps and luminaires is that the modulation depth in them, depending on the driver parameters, can be from 0 to 100%, while in compact fluorescent lamps with high-frequency electronic devices it is no more than 15%. The problem here is that LED products with a high level of luminance flicker do not reach consumers [17]. luminance flicker has a negative impact not only on human well-being and health, but also on other living organisms. The work [18] shows that, first of all, species of animals that lead a diurnal lifestyle are at risk. Few studies of the biological effects of flicker on animals have been conducted, mainly on insects and vertebrates living in captivity. Flicker has been found to affect their behavior and movement patterns. It is concluded that flicker from light pollution, which has not been previously considered, has an impact on the environment and requires research.

The flicker level indicator introduced by the Regulation [10] is the parameter P_{stLM}, where "st" means short-term, and "LM" is the flicker measurement method defined in standards that establish measurement methods and requirements for devices for accurate perception of voltage fluctuations. Flicker in the frequency range 0.05–80 Hz is assessed by the short-term flicker indicator (P_{stLM}) in accordance with IEC TR 61547-1:2020. The visibility indicator of the SVM stroboscopic effect in the frequency range 90–1250 Hz is assessed in accordance with IEC TR 63158:2018.

When studying the impact of LED light sources on the environment using LCA methods, attention was mainly paid to such categories as: global warming potential; toxicity caused by heavy metals; resource depletion, etc. One of the shortcomings of LCA of electric light sources is that when assessing the impact on the environment and human health, the impact of light itself is not taken into account. Based on the analysis of studies on the impact of light on the environment and human health, the CIE in the publication CIE PS 003:2025 recommends improving the environmental friendliness and safety of lighting during the design and installation of lighting systems. It is proposed to avoid undesirable effects. In particular, bright glare, flicker luminance, light that causes discomfort and distraction, as well as other types of light pollution.

From the analysis of literary sources, it can be concluded that at the stage of using LED light sources, the following factors affect the environment, health and well-being of people:

– global warming due to greenhouse gas emissions resulting from the generation of electricity consumed by light sources;

– light pollution, which directly affects living organisms – flicker luminance and stroboscopic effect; glare created by bright light sources and discomfort of the light environment; photobiological danger of blue light for the human retina.

3. The aim and objectives of the study

The aim of the study is to determine the levels of energy efficiency and environmental safety parameters of LED luminaires in accordance with the requirements of the EU Commission Regulations on Ecodesign and Energy Efficiency and international standards. This will make it possible to recommend the most efficient designs of LED sources for use and reduce their negative impacts on the environment and human health at the stage of use.

To achieve this aim, the following objectives were set:

– to conduct a study of the energy efficiency of LED luminaires of directional and non-directional light for compliance with the requirements of the EU Commission Regulations on Ecodesign and Energy Labeling;

– to investigate the level of risks that LED light sources can pose to the environment and human health – flicker luminance and stroboscopic effect, discomfort luminance, photobiological hazard of blue light.

4. Materials and methods

The object of the study is the processes and factors that determine the energy efficiency and environmental friendliness of LED light sources and lighting systems based on them and contribute to reducing negative impacts on the environment and human health. Experimental studies were performed using standard methods for measuring electrical, light, spectral and colorimetric parameters.

Measurements were carried out in the accredited research center for testing electric lamps and technological equipment of the State Enterprise "POLTAVASTANDART-METROLOGY". Measurement methods and product requirements are defined in [10, 11] and European standards EN 13032-4:2015+A1:2019, EN 13032-2:2017, CIE 013.3–1995. The following test equipment and measuring instruments were used for the research (Fig. 1): GO-2000B goniophotometer (EVERFINE Corporation, China), UPRTEK MK350S spectrometer (United Power Research Technology Corp., Taiwan). Main technical characteristics of the GO-2000B goniophotometer: measurement ranges of light intensity 5–150,000 cd, illumination 0.0001–200,000 lux, luminous flux 1–250,000 lm; measurement accuracy ± 7%; rotation angle range from minus 180° to plus 180°. Main technical characteristics of the MK350S spectrometer: wavelength range 380–780 nm; illumination measurement range 1–150,000 lux; accuracy of illuminance determination ± 2.5%, correlated color temperature (CCT) ± 2%, color rendering index Ra ± 1.5%, flicker ± 5% (5–30 kHz).

Commission Regulations EU No. 2019/2020 [10] and No. 2019/2015 [11] set requirements for the energy efficiency of LED light sources, which can be assessed through the maximum permitted power for the declared luminous flux (taking into account the quality of color rendering).

The assessment of the energy efficiency of light sources for general lighting according to Commission Regulation EU No. 2019/2020 [10] is carried out on the basis of information on the measured "useful luminous flux" Φ_{use} and the overall network efficiency η_{TM}. For non-directional sources Φ_{use} is the total luminous flux emitted in a solid angle of 4π steradians (360°). Directional light sources Fuse must have at least 80% of the total luminous flux within a solid angle of π steradians (120°). LED luminaires in which the light sources and control gear are mounted in a single, indivisible housing and cannot be disassembled for separate inspection of the source and control gear are also considered light sources [10].

The maximum power of LED sources for luminous fluxes of 60–82000 lm, according to [10], must not exceed the values calculated using the following expression (1)

$$P_{on\ max} = C \cdot \left(L + \frac{\Phi_{use}}{F \cdot \eta} \right) \cdot R, \quad (1)$$

where C – the basic value of the correction factor. For non-directional LED light sources (NDLS) operating from the mains (MLS), the basic value of C is 1.08, and for directional light sources (DLS) operating from the mains, it is 1.23;

η – the threshold efficiency (lm/W). For LED light sources $\eta = 120$ lm/W;

L – the terminal loss factor (W). For LED light sources $L = 1.5$ W (Table 1 in [10]);

F – the efficiency factor. For LED non-directional light sources $F = 1.0$, and for directional sources $F = 0.85$;

R – a factor that is 0.65 for $R_a \leq 25$ and $(R_a + 80)/160$ for $R_a > 25$.

The energy efficiency classes of light sources according to [11] are determined based on the overall network efficiency η_{TM}. This coefficient is calculated by dividing the useful luminous flux Φ_{use} (lm) by the power in full burning mode (W), multiplied by the coefficient F_{TM}, which takes into account the type of source, as well as the method of power supply.

The risks of photochemical damage to the retina by blue light with a wavelength of 435–440 nm from LED sources were investigated in accordance with the standardized methods EN 62471:2008, IEC/TR 62778:2014.

The hazard-weighted energy luminance of blue light LB was measured using the OST 300 test equipment complex (EVERFINE Corporation, China). The OST 300 spectroradiometric system (Fig. 1) contains a monochromator, a photometric detector, a system for measuring the size of light sources that simulates the human eye in the field of view of 100, 11 and 1.7 mrad, diaphragms for limiting the field of view.

The system is used to measure the spectral distribution of power, luminance, irradiance, illumination, apparent size of the light source, color temperature, color rendering index and other parameters. The device is equipped with a large aperture lens that allows to measure the object under study from small and large distances and a CCD matrix with a resolution of more than one million pixels. Luminance in different fields of view (1.7 mrad, 11 mrad and 100 mrad) can be measured simultaneously.

Main technical characteristics of the OST300 complex: optical rail 6 m; accuracy of measurement of illuminance and energy illuminance ± 5%, luminance and energy illuminance ± 5%; wavelength range 200–3000 nm; wavelength setting accuracy – 0.2 nm. Special software allows calculating based on spectral measurements the energy illuminance LB and energy illuminance Es, taking into account the blue light hazard weight function B(λ), CCT and other parameters.

The discomfort glare created by LED luminaires was studied in accordance with the recommendations of CIE 117-1995, CIE 232:2019 and [20].

To assess the levels of discomfort glare of light sources in rooms, the generalized UGR indicator proposed in CIE 117–1995 is used. The result of the UGR calculation is a number with values from 10 to 30, with lower values indicating less discomfort caused by glare. A UGR level of ≤ 19 is considered acceptable for most indoor spaces (offices, classrooms, etc.). The recommended UGR threshold values are characterized as < 10 – imperceptible level of discomfort; < 13 – barely noticeable; < 16 – noticeable; < 19 – satisfactory; < 22 – limited satisfactory; > 25 – noticeable; > 28 – significant.

Several models have been proposed to predict discomfort from glare caused by outdoor lighting systems [21, 22], but no single generally accepted method has yet been developed. Existing discomfort assessment models use different stimulus characteristics that need to be measured for different areas of application (for pedestrian areas, for areas with low traffic speed, for pedestrian crossings, etc.). The following indicators are used: average luminance of the light source, maximum luminance, background luminance, projection area of the source, solid angle of the source, effective luminance, luminous intensity, etc. The CIE instructed the relevant technical committee to develop a model for assessing the feeling of discomfort glare for outdoor lighting, which can be a unified glare rating (UGR) model.

To take into account the influence of uneven luminance distribution in accordance with the recommendations of CIE 232:2019, the concept of "effective radiation area" was introduced. The effective radiation area of LED light sources in calculations includes surfaces with a luminance higher than 500 cd/m^2.

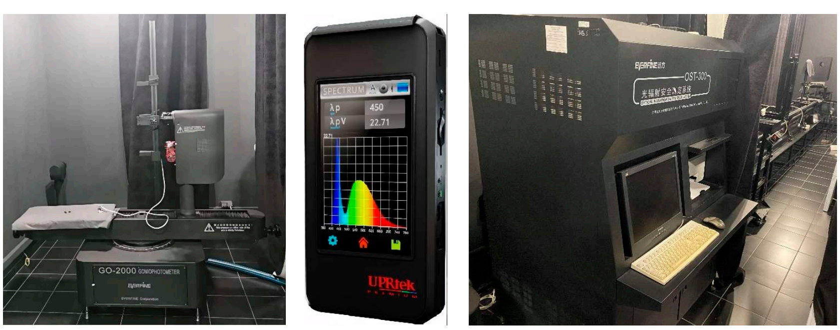

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Fig. 1. General view of the test equipment and measuring instruments used in the research: *a* — GO-2000B goniophotometer; *b* — UPRTEK MK350S spectrometer; *c* — OST 300 complex

In the studies, the area with a luminance higher than 500 cd/m^2 was measured using the OST 300 complex.

Fig. 2 shows an example of uneven distribution of source luminance and areas selected for measurement at different angles of the field of view.

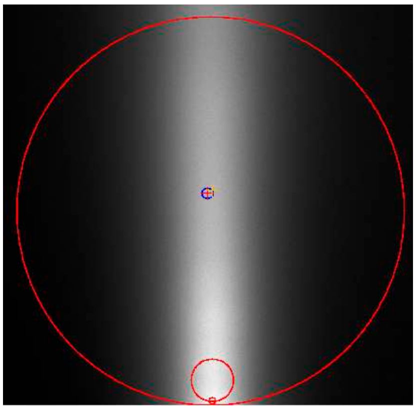

Fig. 2. Example of uneven distribution of light source luminance and areas allocated for measurement at different angles of the field of view

To estimate the unified glare rating UGR of LED luminaires with uniform luminance distribution, the expression (2) can be used

$$UGR = 8 \cdot \lg\left(\frac{0.25}{L_B} \cdot \sum_{i=1}^{N} \frac{L_i^2 \cdot \omega_i}{\rho_i^2}\right), \quad (2)$$

where L_B – the background luminance, which depends on E – vertical illuminance, directed towards the observer's eye, cd/m^2; L_i – the luminance of the i-th luminaire, directed towards the observer's eye, cd/m^2; ϖ_i – the solid angle of the emitting part of the i-th luminaire in the direction of the observer's eye, rad; N – the number of luminaires in the lighting installation; ρ_i – the Guth index for each individual luminaire, which depends on the direction of the line of sight.

Luminaires with non-uniform luminance of the radiating surface according to CIE 232:2019 are evaluated by the formula (3)

$$UGR' = 8 \cdot \lg\left(\frac{0.25}{L_B} \cdot \sum_{i=1}^{N} K^2 \cdot \frac{L_s^2 \cdot \omega}{\rho_i^2}\right), \quad (3)$$

where $K^2 = \frac{L_{eff}^2}{L_S^2} \cdot \frac{\omega_{eff}}{\omega}$; L_{eff} – the effective luminance; ϖ_{eff} – the effective solid angle of the total luminous area with L_{eff}; L_S – the average luminance of the luminaire; ϖ – the solid angle in which the light of the entire luminaire is emitted. One of the methods for determining the effective luminance L_{eff} is based on the nature of the luminances. For L_{eff} calculations, the luminance within the effective area A_{eff} is taken, which is determined by the angle ϖ_{eff}. The ratio A_{eff} / A is called the effective area coefficient, which is proportional to ϖ_{eff} / ϖ.

The flicker and visibility indicators of the stroboscopic effect (P_{stLM} and SVM), which are regulated by the EU Commission Regulation on Ecodesign No. 2019/2020 [10], are a type of light pollution. They are determined according to the standards IEC TR 61547-1:2020, IEC TR 63158:2018. The UPRTEK MK350S spectrometer was used for measurement.

The following conditions were adopted to evaluate the levels of luminance flicker P_{stLM}:

– at $P_{stLM} = 1$, the tested light source has a flicker level that is detected by the observer with a probability of 50%, such as in 60 W incandescent lamps;

– at $P_{stLM} < 1$ – the light source has a flicker level lower than in 60 W incandescent lamps;

– at $P_{stLM} > 1$ – the flicker level is higher than in incandescent lamps and is easy to detect.

As for the assessment of the stroboscopic effect, an objective method for measuring the stroboscopic effect visibility (SVM) is proposed in the IEC TR 63158:2018 standard. The conditions for the occurrence of the stroboscopic effect considered in this document are limited to the assessment at illuminances greater than 100 lux and at moderate object speeds (< 4 m/s).

The following conditions are adopted for the assessment of the visibility of the stroboscopic effect SVM: at $SVM = 1$, the stroboscopic effect created by the light modulation is at the threshold of visibility. This means that the average observer can detect it with a probability of 50%. If the value of $SVM < 1$, then the probability of detection is less than 50%, and if $SVM > 1$, then the probability will be higher than 50%.

5. Results of research on the parameters of energy efficiency and environmental friendliness of LED luminaires of directional and non-directional light

5. 1. Research on the energy efficiency of LED luminaires of directional and non-directional light

This work investigated the energy efficiency of LED luminaires of non-directional and directional light for lighting premises of industrial and public buildings, offices, educational institutions and outdoor lighting. There are many designs of LED luminaires for various purposes. The most typical ones that are widely used were selected for research. Table 1 and Fig. 3–6 show the results of measurements and calculations and provide basic information about the parameters of the studied luminaires. Sources of directional light include LED lamps and luminaires with concentrated and deep light curves (LC). Light sources with other LC types, including cosine, are sources of non-directional light. Fig. 3–6 show the spatial distributions of the luminous flux of some of the studied luminaires according to the LCSGRAPH classification (Luminaire classification system – LCS) with information on the type of LCS and the percentage of "useful luminous flux" U_{se}, which is taken into account when determining the energy efficiency of the sources [11].

In the luminaires for directional and non-directional light, except for No. 5, 10, medium and high-power LEDs with lens and reflective optics were used. These luminaires are designed for lighting industrial premises with high ceilings (No. 1–4) and outdoor lighting (No. 6–9). In luminaires No. 5, 10, low-power LEDs and prismatic and opal light diffusers were used. One of the main requirements for such luminaires is to ensure uniform distribution of the luminance of the radiating surface (average values up to 5000 cd/m^2). These luminaires are designed for lighting public buildings, educational and medical institutions, offices, etc.

All the studied luminaires, in terms of energy efficiency, meet the requirements of the EU Commission Regulations 2019/2015 and 2019/2020 [10, 11].

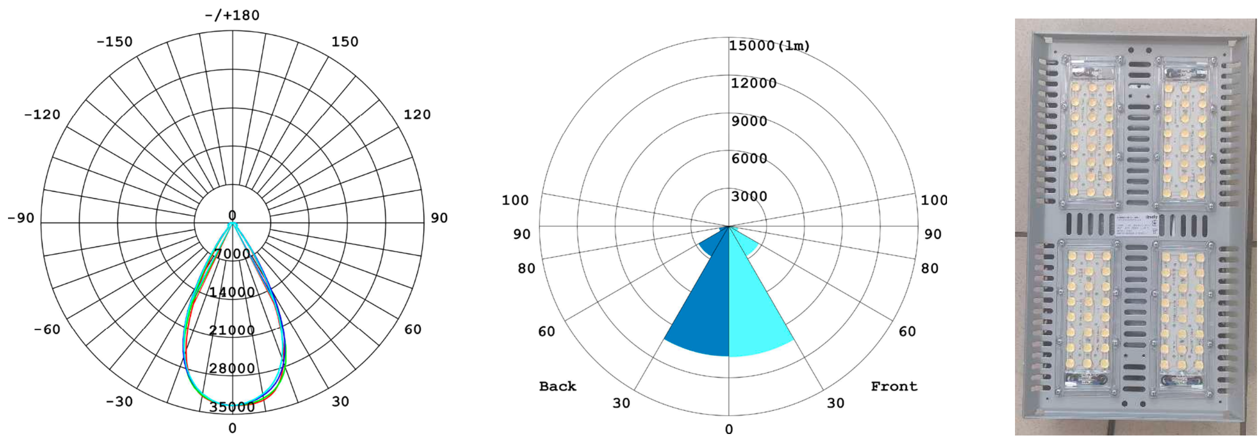

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Fig. 3. Luminous intensity curve and spatial distribution of the luminous flux of an LED luminaire for lighting industrial buildings (directional light source):
a — luminous intensity, cd (type of luminous intensity curve — deep, I_{max} — in the angle range 0–30°);
b — luminous flux, lm (luminous flux within the angle range 120° — 93.3%);
c — appearance of the luminaire under study

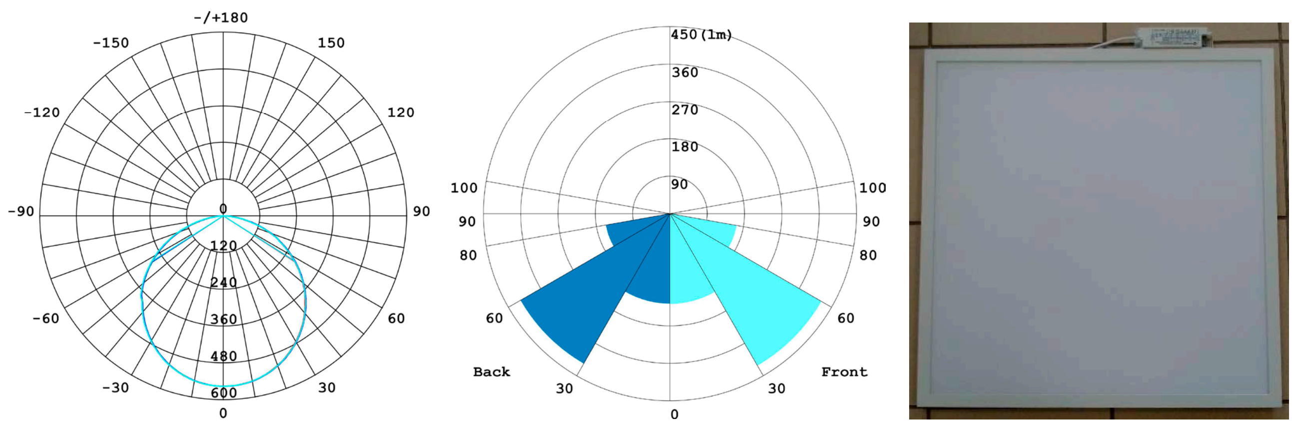

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Fig. 4. Luminous intensity curve and spatial distribution of the luminous flux of a reflected light LED luminaire for office lighting (non-directional light source):
a — luminous intensity, cd (LC type is cosine, I_{max} is in the angle range 0–35°);
b — luminous flux, lm (luminous flux within the angle 120°— 78.3%); *c* — appearance of the studied luminaire

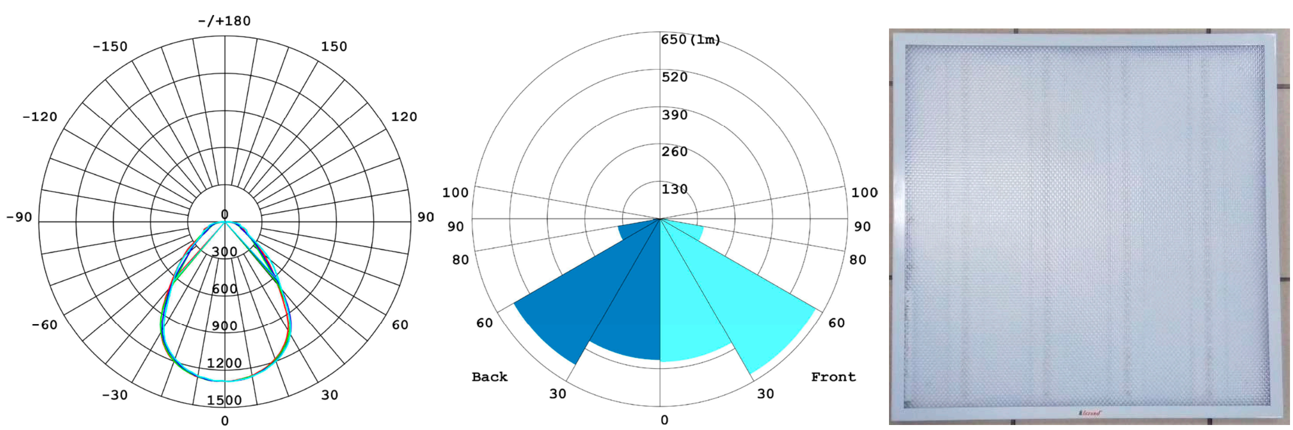

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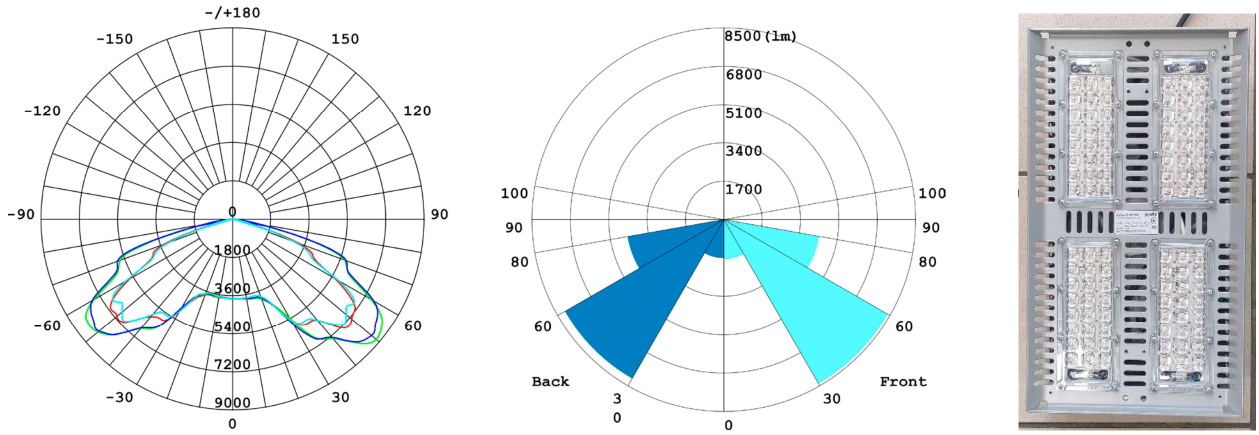
Fig. 5. Luminous intensity curve and spatial distribution of the luminous flux of an LED luminaire for office lighting with a prismatic light diffuser (directional light source):
a — luminous intensity, cd (LC type is deep, I_{max} is in the angle range 0–30°);
b — luminous flux, lm (luminous flux within the angle 120° — 86.9%); *c* — appearance of the studied luminaire



a *b* *c*

Fig. 6. Luminous intensity curve and spatial distribution of the luminous flux of an LED luminaire for outdoor lighting (non-directional light source): *a* – luminous intensity, cd (LC type is semi-wide, I_{max} is in the angle range of 35–55°); *b* – luminous flux, lm (luminous flux within the angle of 120° – 69.1%); *c* – appearance of the studied luminaire

Table 1

Measurement results and calculations (based on measurement data) of maximum power and energy efficiency classes of LED luminaires for directional and non-directional light

Luminaire number	Power P_{on}, W	Total luminous flux Φ, lm	Percentage of luminous flux in a solid angle of 120, %	Types of luminous intensity curve	Useful luminous flux, Φ_{use} (lm)	Color rendering index R_a, relative units	Maximum permissible power, $P_{on\ max}$, W	Total network efficiency η_{TM}, lm/W	Energy efficiency class according to [11]
Directional light sources									
1	198	29978	92.9	deep	27850	80.4	338	165	C
2	164.7	23176	94.2	deep	21830	80.1	265	156	D
3	197.4	28237	83.7	deep	23634	73.1	274	141	D
4	197.3	29058	93.4	deep	27140	73.0	278	162	C
5	45.1	4510	82.0	deep	3700	80.2	47	97	F
Non-directional light sources									
6	197.4	28960	69.7	half-wide	28960	70.8	248	147	D
7	59.2	10052	76.2	wide	10052	72.2	87	170	C
8	102.2	16531	76.1	wide	16531	72.4	167	162	C
9	106.8	14420	70.0	half-wide	14420	72.8	126	135	D
10	39.3	3968	78.0	cosine	3968	86.9	39	101	F

In order to assess the level of reduction in the luminous efficiency of luminaires for outdoor lighting during operation due to their contamination, measurements of light parameters were carried out before maintenance (before cleaning the luminaires) and after maintenance. The reduction in luminous efficiency due to contamination of an LED luminaire after 2.5 years of operation in an outdoor lighting system is 16%. The indicator of the level of contamination is determined through the planned service life by the ratio of the luminous efficiency (or luminous flux) before cleaning the luminaire to the corresponding indicators after cleaning and is estimated in percentages. Significant loss of light due to contamination of luminaires increases the relevance of periodic maintenance of LED lighting systems for all areas of application.

5. 2. Research on the level of light risks created by LED sources

Lighting using LEDs is relatively new compared to other types of light sources and it is important to take into account all potential impacts on human health and the environment.

Comparative studies of the luminance distribution on the radiating surface of Armstrong-type ceiling luminaires with opal and prismatic diffusers have been conducted. The best uniformity of luminance on the radiating surface is created by LED luminaires of reflected light. Fragments of the general appearance of the radiating surface of luminaires of reflected light and luminaires with opal and prismatic diffusers are shown in Fig. 7.

When using opal diffusers, the LC of the luminaires corresponds to the cosine type and the luminaires belong to sources of non-directional light. The use of light diffusers with different sizes of prismatic relief on their surface brings the LC of the luminaires closer to the deep type (the percentage of luminous flux in a solid angle of 120° exceeds 80%) and they should be classified as a source of directional light. Luminaires with cosine LC are inferior in efficiency to luminaires with deep LC for creating horizontal illumination, but they are more effective for providing vertical illumination, which is very important for the implementation of integrated lighting projects.

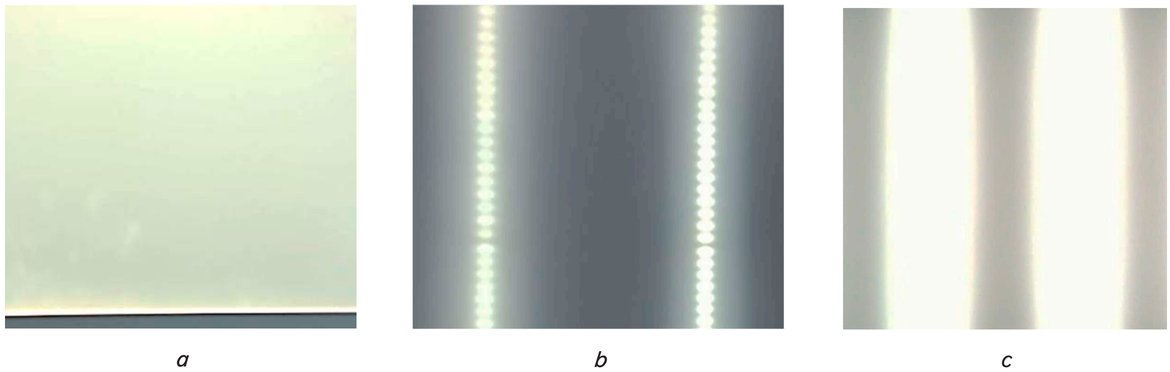


Fig. 7. Fragments of the general appearance of the radiating surface: *a* — a luminaire of reflected light; *b* — a luminaire with a prismatic diffuser; *c* — a luminaire with an opal diffuser

An opal diffuser with a luminous flux per unit area of the diffuser within 0.8–1.6 lm/cm^2 creates a LC close to the cosine, with an average luminance of the radiating surface of up to 5000 cd/m^2. The peak luminance of individual "light spots" in this case can be 7000–8000 cd/m^2, and the minimum luminance of the radiating surface is not lower than 500 cd/m^2.

The use of prismatic diffusers creates a directional-diffuse scattering of light and the LC thus approaches the deep type. The peak luminance on the radiating surface of the luminaire can reach values of 10,000 cd/m^2, and the minimum luminance decreases to 300–200 cd/m^2. Bright areas of the radiating surface of luminaires cause discomfort and disability glare, especially in cases where their peak luminance significantly exceeds the average value.

For luminaires with opal diffusers, in which the minimum luminance of the radiating surface exceeds 500 cd/m^2, the unified glare rating (UGR) is determined using expression (2).

For luminaires in which part of the radiating surface has a luminance lower than 500 cd/m^2, it is necessary to determine the effective radiation area and the effective luminance generated by this area. To calculate the corrected unified glare rating (UGR'), expression (3) must be used.

Studies were conducted on the change in the generalized discomfort index $\Delta UGR'$caused by the uneven distribution of luminance on the radiating surface of a luminaire with a prismatic light diffuser in comparison with a luminaire with reflected light.

The average luminance of the luminaire Ls was determined by measuring the luminous intensity directed at the observer and the emitting area of the luminaire A.

Based on the data of measuring the luminous intensity, the distribution of luminance on the radiating surface of the luminaires, the effective area of the luminaire radiation, the maximum and average luminance were determined and the calculated value of the coefficient $K^2 = \frac{L_{eff}^2}{L^2} \cdot \frac{\omega_{eff}}{\omega}$ and the level of increase in the discomfort index $\Delta UGR' = 8 \cdot \lg K^2$ caused by the uneven distribution of luminance [20]. The results are summarized in Table 2.

The uneven distribution of luminance using a prismatic diffuser increases the value of the generalized discomfort index UGR' by 3 units, which reduces the rating of light comfort due to glare by the same amount.

Measurements of the energy luminance of LED luminaires (taking into account the blue light hazard weight function) and calculations of their photobiological safety level were carried out in accordance with the requirements of EN 62471:2008, IEC/TR 62778:2014. Measurements of the maximum luminance L_V and effective energy luminance L_{eff} were carried out using the OST300 equipment complex in the field of view of 1.7 mrad and 11 mrad. The results of measurements and calculations are given in Table 3.

Ceiling luminaires of directional and non-directional light with low-power LEDs with an average luminance of the radiating surface below 5000 cd/m^2 belong to the general group RG0. Luminaires of non-directional and directional light with medium and high-power LEDs belong to the risk group RG1.

Luminaires for lighting industrial premises and outdoor lighting are mounted at fairly high distances from the lighting objects and the illumination levels they create do not exceed 500 lux. They do not pose a photobiological hazard, but the luminance levels must be significantly reduced, as this creates glare and discomfort.

The studies of flicker levels P_{stLM} and visibility level of stroboscopic effect SVM were carried out in accordance with the requirements of the EU Commission Regulation No. 2019/2020 [10] and the standards IEC TR 61547-1:2020, IEC TR 63158:2018, using UPRTEK MK350S. Examples of measurements of individual luminaire samples are given in Table 4.

Table 2

Estimation of the change in the generalized discomfort index $\Delta UGR'$ caused by uneven bright luminance ness

Luminaire characteristics	Average luminaire luminance L_s, cd/m^2	Effective luminance L_{eff}, cd/m^2	Effective area coefficient A_{eff}/A, relative units	Calculated value of coefficient K^2, relative units	Level of increase in discomfort index $\Delta UGR' = 8 \cdot \lg K^2$, relative units
Reflected light luminaire	5.1	5.1	1	1	0
Luminaire with prismatic light diffuser	3.9	9.1	0.45	2.4	3

Table 3

Results of measurement and calculation of the level of photobiological hazard of directional and non-directional light

Luminaire characteristics	Correlated color temperature (CCT), K	Energetic luminance L_B, W/^{2}av	Luminance, L_V, cd/m^2	Maximum safe continuous exposure time, s	Risk group RG
Non-directional light luminaire for indoor lighting, cosine LC	3784	2.1	$5.1 \cdot 10^3$	$4.8 \cdot 10^5$	0
Directional light luminaire for indoor lighting with prismatic diffuser, deep LC type, diffuse directional	3746	2.5	$5.7 \cdot 10^3$	$4.1 \cdot 10^5$	0
Non-directional light luminaire for outdoor lighting with lens optics, wide LC type	3975	1904	$2.7 \cdot 10^6$	650	1
Non-directional light luminaire for outdoor lighting with lens optics, semi-wide LC type	3945	2127	$3.0 \cdot 10^6$	345	1
Directional light luminaire for industrial lighting with reflective mirror optics, deep LC type	5480	2339	$2.8 \cdot 10^6$	240	1

Table 4

Measurement results of the flicker parameters P_{stLM} and visibility index of the stroboscopic effect SVM of the studied LED luminaires for indoor and outdoor lighting.

Product name	Sample number	Modulation depth, %	P_{stLM}, relative units	SVM, relative units
Luminaire for indoor lighting	5	1.1	0.0621	0.0107
	10	2.0	0.0785	0.0103
Luminaire for outdoor lighting	7	5.9	0.0910	0.0884
	9	10.8	0.2726	0.2125

All the studied luminaires meet the requirements [10] – $P_{stLM} < 1$, SVM < 0.4.

6. Discussion of the results of the study of energy efficiency and environmental friendliness of LED luminaires for directional and non-directional light

Ecodesign is a form of environmental regulation that provides for measures to reduce electricity consumption by lighting systems and reduce the impact of energy-consuming products on the environment and human health. It focuses on the stages of life cycles that have the greatest impact on the environment. For light sources, the greatest impact occurs at the use stage (due to electricity consumption).

In 2019, the EU increased the requirements for energy efficiency and environmental friendliness of LED light sources by establishing new energy and environmental performance limits in Commission Regulation EU No. 2019/2020.

Comparing the energy efficiency of LED luminaires for directional and non-directional light (Table 1), it is possible to conclude that it depends mainly on the light output of the LEDs and light losses in optics and light diffusers. High- and medium-power LEDs have a light output 1.3–1.5 times higher than low-power ones, and the loss of luminous flux when using light diffusers of various types is 15–45%. With the same useful luminous flux, non-directional and directional luminaires using high-power LEDs have approximately the same efficiency (η_{TM} within 135–170 lm/W) and correspond to energy efficiency classes D and C. One of the phenomena that limits the normal functioning of the visual system is glare. Glare is created by light sources with high luminance. They cause a decrease in the ability to see objects near the light source or its reflection and can create physical effects (headaches, migraines, and discomfort). The standardized method for assessing the levels of discomfort glare is the unified glare rating (UGR).

To reduce the luminance of the radiating surface of the luminaire, light diffusers of various designs are used.

Ceiling luminaires with a radiating surface size of 595 × 595 mm, in which low-power SMD (Surface-Mount Device) LEDs and various types of light diffusers are used to limit the average luminance to 5000 cd/m^2, have a luminous energy efficiency η_{TM} up to 100 lm/W (energy efficiency class “F”).

In [10], the requirements for the luminance of LED sources are not established, but such requirements are established in the lighting standards ISO/CIE 8995-1:2025, EN 12464-1:2021, EN 12464–2:2024. Energy efficiency significantly depends on the level of luminance on the radiating surface of the luminaire, therefore, ensuring high energy efficiency indicators at safe luminance levels of LED luminaires is one of the tasks of improving the ergonomics of luminaires. LEDs, as a rule, are sources of directional light with a small radiation area and high luminance. The bright light of LEDs can cause not only a disability and discomfort effect on human eyes, but also pose a danger to the retina. The degree of damage depends on the luminance of the light source, its angular size, radiation spectrum and duration of exposure. Depending on these factors, retinal damage can take various forms: from photoretinitis and retinal burns to macular degeneration [23].

Light emitted in the wavelength range of 400–500 nm (with a maximum of around 435–440 nm) causes photochemical effects on the retina. This range corresponds to blue light, and the hazard associated with this spectral range is therefore called blue light hazard. The International Commission on Illumination [24] provides clarification on the term “blue light hazard”. It should only be used when considering the photochemical risk of retinal damage (photomaculopathy), usually associated with staring at bright light sources. General requirements for the classification and methods for assessing the photobiological safety of lamps and lamp systems are set out in EN 62471:2008. For LED lamps and lamp systems used for general lighting, explanations and guidance on the assessment of the blue light hazard are provided in IEC/TR 62778:2014.

The results of the study of the photobiological hazard of blue light from LED luminaires for various purposes (Table 3) show that luminaires for indoor lighting belong to the RG0 risk group (does not carry any photobiological hazard). Luminaires for outdoor lighting and lighting of industrial facilities using powerful LEDs and lens and mirror optics belong to the RG1 risk group (low risk). But these luminaires are mounted at large distances from the lighting objects and do not pose real threats of photobiological hazard to humans.

One of the negative effects created by electric light sources is luminance flicker. In incandescent lamps and discharge lamps, luminance flicker occurs due to a change in the supply voltage in the AC network over a period. The luminance characteristics of LEDs mainly depend on the driver (power source) and the light flux control system (dimmers). The flickering of LED luminance can theoretically be reduced to zero by ensuring the stability of the power supply and high-frequency electronic devices for regulating the luminous flux (at frequencies exceeding the sensitivity interval of flicker perception – more than 1.2 kHz). It should also be noted that LED lighting can create a depth of luminance modulation higher than that of discharge lamps [17].

To describe the environmental impact of light on the environment and human health, it is difficult to find a general indicator of stability, therefore it is advisable to consider light pollution as an environmental effect by individual types. For example, flicker – by the short-term indicator P_{stLM}; the level of the stroboscopic effect – by the indicator of the visibility of the stroboscopic effect SVM; the photobiological hazard of blue light – by the risk group RG, etc. For a practical assessment of the impact of light pollution on the environment and minimizing this impact, it is necessary to develop guidelines that could be used by ecologists, lighting managers and other specialists at different levels.

It is advisable to assess the negative impact of light due to the risks posed by LED lighting systems (glare, photobiological hazard, luminance flicker, stroboscopic effect) based on the limit values of these parameters established by EU Commission Regulations and international standards.

The following measures are recommended to reduce the negative impact of LED lighting systems on the environment.

When designing, manufacturing and operating lighting systems, it is necessary to use LED sources that meet the energy efficiency parameters of the EU Commission Regulations on Ecodesign No. 2019/2020 and Energy Labeling No. 2019/2015. These regulations establish requirements that meet the state of the art. The regulations, taking into account the technical progress of LED technology, are periodically reviewed. During the review, the feasibility of establishing stricter requirements for energy efficiency is assessed, and indicative reference parameters with the best characteristics available on the market are also established.

LED light sources must meet the following environmental requirements:

– the risk of blue light hazard for indoor lighting (office, educational, medical, residential, etc.) should not exceed group RG0. The risk of blue light hazard for outdoor and industrial lighting should not exceed group RG1;

– the level of flicker luminance P_{stLM} and visibility of the stroboscopic effect SVM should not exceed the requirements established by Commission Regulation (EU) No. 2019/2020;

– the UGR discomfort indicators created by luminaires should not exceed the recommendations of the ISO/CIE 8995-1:2025 standard for specific areas of lighting.

To limit irrational lighting costs and its negative impact on the environment, it is advisable to use timers, sensors, automatic lighting control systems, screen and direct light onto the lighting object, etc. [25].

To reduce light pollution, it is necessary to introduce restrictions on lighting of areas, light intensity levels and duration of lighting, reduce light penetration into homes at night, reduce glare, etc. [26].

In 2019, the European Commission launched a new publicly available database that allows consumers to compare the energy efficiency class of various household products and other characteristics. The European Product Registry for Energy Labelling (EPREL) opens new ways to help consumers improve energy efficiency through detailed information on energy-labelled products [12].

These measures can be implemented through amendments to regulatory documents, the development of health and sanitary recommendations to reduce negative impacts on the environment and human health, and guidelines for the design and maintenance of lighting systems.

In conclusion of the analysis of the research results, it should be noted that in recent years, due to the implementation of the requirements of the Ecodesign Regulations, there has been a significant increase in the energy efficiency and environmental friendliness of LED light sources. It is worth noting the increase in color uniformity (SDCM < 6), the increase in the uniformity of luminance distribution on the radiating surface of the luminaires, and the increase in the stability of the luminous flux during the service life. LED sources require further improvement in the following areas: reducing glare and improving the quality of color rendering; reducing the negative impact of LED light sources on circadian rhythms due to the large proportion of blue light in their spectrum.

The results obtained will be used in the preparation of practical medical and sanitary recommendations for the use of LED light sources in lighting systems for various purposes and making changes to state building codes.

It should be noted the lack of the study on light pollution created by outdoor lighting systems, illuminated advertising, and vehicles. It is planned to expand research on light pollution, as well as on integrated lighting, the main requirements for which are formulated in ISO/CIE 8995-1:2025.

7. Conclusions

1. LED luminaires of various designs were studied for compliance with the requirements of the EU Commission Regulations on ecodesign and energy labelling. It was shown that LED luminaires of non-directional and directional light using medium and high-power LEDs have high luminous efficacy η_{TM} 135–170 lm/W, and meet energy efficiency classes D and C. The luminaires meet the requirements for lighting industrial buildings, outdoor lighting and other objects. However, a significant part of these luminaires has a color rendering index of less than 80 and high luminance. Luminaires with low-power LEDs, with a light load per unit area of the light diffuser of 0.8–2 lm/cm^2, have a luminous efficacy η_{TM} 100 lm/W and belong to energy efficiency class F.

The luminaires meet the minimum requirements of the Energy Efficiency Regulations. They can create a high-quality lighting environment and be used to illuminate educational and medical institutions, offices, residential premises and other facilities.

2. Luminaires with low-power LEDs, in which the light load on the diffusers is within 0.8–2 lm/cm^2, have a luminance of the radiating surface up to 5000 cd/m^2 and correspond to the photobiological safety level of risk group RG0. Luminaires with powerful LEDs and lens optics for lighting industrial buildings and outdoor lighting correspond to the photobiological safety level of risk group RG1. There is a high peak luminance on the radiating surface of individual luminaires, exceeding 1 Mcd/m^2. Such luminaires can be used for outdoor lighting and lighting industrial premises with high ceilings. All tested luminaires meet the requirements of EU Regulation 2019/2020 for a safe level of flicker and visibility of the stroboscopic effect. The short-term flicker index $P_{stLM} < 1$, and the visibility index of the stroboscopic effect $SVM < 0.4$. The best luminance uniformity and level of comfort of the lighting environment are created by LED luminaires of reflected light. Luminaires with opal and prismatic diffusers create a satisfactory luminance distribution. The increase in the generalized discomfort index created by these luminaires with prismatic diffusers can be more than 3 units compared to luminaires of reflected light, and partially worsen the comfort of the lighting environment. Luminaires with powerful LEDs and lens optics create high generalized discomfort indicators on the lighting object, so their use is limited to outdoor and industrial lighting.

Conflict of interest

The authors declare that they have no conflict of interest regarding this study, including financial, personal, authorship or other, that could influence the study and its results presented in this article.

Financing

The study was conducted without financial support.

Data availability

Data will be provided upon reasonable request.

Use of artificial intelligence

The authors confirm that they did not use artificial intelligence technologies when creating the presented work.

Authors' contributions

Vasyl Nazarenko: Conceptualization, Writing – reviewing & editing; **Viktor Sorokin:** Conceptualization, Validation, Formal analysis; **Demyd Pekur:** Software, Data Curation; **Svitlana Shpak:** Resources, Writing – reviewing & editing, Management, Project Administration Funding; **Iuliia Basova:** Research, Visualization, Writing – original draft; Funding acquisition; **Sabir Bagirov:** Research, Formal analysis, Visualization, Funding acquisition; **Gregory Kozhushko:** Methodology, Formal Analysis, Research, Writing – Original Draft, Writing – Reviewing and Editing, Supervision.

Acknowledgements

The authors express their sincere gratitude to the National Academy of Medical Sciences of Ukraine and the State Enterprise "Poltava Regional Scientific and Technical Center for Standardization, Metrology and Certification" for providing the material and technical base for conducting the study.

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