Measures to Improve the Energy Efficiency of Street Lighting Systems in the Kharkiv City

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Abstract
High-quality street lighting improves visual perception of the road and provides for a significant decrease in the number of road accidents. It has been established that the total number of accidents can be reduced by 30% for national roads and by 45% for especially hazard areas (e.g., at intersections). Doubling of the average luminance of the road surface significantly reduces the number of accidents in the dark and twilight. Sufficient street lighting contributes to: reducing electricity consumption; decreasing operating costs; improving the environmental situation; promoting business, tourism and investment activity; decreasing the number of criminal offenses. The analysis of recent research and publications helped choose the best European practices which can be used to improve the outdoor lighting in Ukraine. The street lighting network is continuously growing and being modernized. Different types of light sources are being used in the network to illuminate the city. Today, high-pressure lamps (HPS) are leading. They are increasingly replaced by LED light sources. Not a small share is accounted for by metal-halide lamps. The smallest number of light sources in the street lighting system, high-pressure mercury and compact fluorescent lamps (CFLs). To increase the efficiency of the street lighting system and reduce energy consumption for its operation, measures for its reconstruction and modernization are required. For this purpose, it is necessary to address the following problems: high level of obsolescence and physical wear and tear of system elements; inefficient use and high losses of electricity at the stages of transportation and consumption, due to the use of obsolete and worn-out equipment; suboptimal distribution of the utility capacity, which leads to ineffective use of the existing lighting system; low efficiency of the street lighting control system, due to the lack of electric meters and remote monitoring and control of the street lighting. Introduction of energy-saving types of light sources is one of the ways to modernize the existing street lighting system. It is necessary to replace old lighting fixtures, which have already exhausted their life span, by low energy-saving light sources (replace CFLs by LEDs), use automatic control systems. All this in turn will help reduce energy costs by 60%. To improve energy efficiency of the street lighting system, it is also recommended to carry out the replacement of electromagnetic ballasts by electronic ones. The employment of electronic ballasts, e.g., in case of using HPS 250 lamps, allows to save approximately 255 kWh/year. Considering that the price per kW of electric energy is UAH 2.68, one luminaire helps save the amount of UAH 683.4 per year.

INTRODUCTION

It is known that high-quality street lighting improves visual perception of the road and provides for a significant decrease in the number of road accidents. It has been established that the total number of accidents can be reduced by 30% for national roads and by 45% for especially hazard areas (e.g., at intersections) [1–9].

The same results were obtained during the studies of the relationship between street lighting and road accidents [10–12], carried out at the initiative of the International Commission on Illumination (CIE). Doubling of the average luminance of the road surface significantly reduces the number of accidents in the dark and twilight. This was clearly demonstrated by experiments commissioned by the German
Ministry of Transport and carried out on ten road sections in six major cities. The number of road accidents decreased by 28%. The number of road accidents involving pedestrians, cyclists, and motorcyclists declined by 68%, and that of other accidents by 45%.

In addition, high-quality street lighting contributes to:
- reducing electricity consumption (which is extremely important in the context of the economic crisis);
- decreasing operating costs;
- improving the environmental situation (reducing heating of the atmosphere, harmful emissions (waste disposal), light pollution);
- promoting business, tourism and investment activity.

Well-designed street lighting can also help prevent crime. Practice shows that acts of violence and crimes against property mainly take place in dark places, where criminals feel comfortable since under such circumstances, they are difficult to see and remember, and potential victims are practically helpless [13, 14]. An increase in the level of horizontal illumination in pedestrian zones, which is also accompanied by an increase in vertical illumination, contributes to a better visual space perception.

Analysis of recent studies and publications has shown that the designing of street lighting systems in accordance with the German standard DIN EN 13201-3 is one of the best positive European practices [15]. The main goal of this standard is to improve the visibility of streets and roads for all people using them. The implementation of its recommendations ensures the correct visual perception of the road surface and its boundaries, points of confluence and intersection of roads, direction of movement and possible obstacles, location of road users and their movements. In the end, a regime of safe continuous urban traffic is achieved.

Ukrainian and foreign authors pay much attention to mesopic photometry and its relationship with street lighting. For example, in works [1-9, 16-18], the issue of achieving safety of people in the streets in the dark with the help of artificial lighting is analyzed. To determine the required power of lamps for replacing existing luminaires, it is recommended to use a mesopic photometric system, which allows performing calculations using the S/P ratio. This ratio is considered to be an important characteristic of light sources.

The investigations of energy efficiency and energy saving is presented in works of Carli R., Dotoli M., Pellegrino R., Beccali M., Bonomolo M., Ciulla G., Galatoto A., Lo Brano V., et al. [19-25].

The existing street lighting systems have already exhausted their life span and become inefficient, which results in insufficient street lighting and irrational consumption of electricity.

The aim of the paper is to present measures for improving energy efficiency of street lighting systems in Kharkiv.

STREET LIGHTING CLASSIFICATION

Lighting of roads and adjacent areas is divided into the following subtypes [2, 15, 20, 26-33]:
- for the main transport routes. In such large-scale systems, powerful lamps (200-400 W) and lamps with reflectors, which concentrate the flow of light on the road, are used. They are installed on posts (poles) at a sufficient height. There are special requirements for fixing lamps and anchoring foundations of lamp posts;
- for by-pass routes. In these systems, 70–250 W lamps are employed. Along with reflex lighting, diffused lighting can be used. For this purpose, transparent relief shades are installed, which scatter the rays over a large area;
- for sidewalks, park and pedestrian zones, bike paths, transport stops. In such systems, diffused light from lamps with a power of about 40–125 W is used. The shape of the shade can be spherical or cylindrical. For better light diffusion, the shades can be equipped with additional transparent relief rings;
- lighting of information signs, which can be external and internal (built into the object). For this purpose, special lamps and spotlights are used;
- architectural highlighting, which needs to be thoroughly designed by landscape and architectural designers. Also, special lighting facilities are used, often of a special shape with decorative fastening elements.

CURRENT STATE OF STREET LIGHTING SYSTEMS IN KHARKIV

The street lighting network is continuously growing and being modernized.

In 2017, the total length of street lighting networks was 2498 km (Fig. 1, Tabl. 1), of which 51.2% were cable networks and 48.8% overhead networks.

The number of luminaires in the property of Miskivitlo, the municipal enterprise providing operation and servicing of street lighting networks in Kharkiv, was 80,822 ths. The distribution of luminaires by light source is shown in Fig. 2. The number of operative lighting fixtures by type of light source was 79,994 ths, that of non-operative ones comprised about 1.1% of the total amount.
The city installed 608 intelligent street lighting systems (remote control and GSM modules).

The number of meters used to measure electrical energy consumed by the city’s street lighting systems (including variable-rate electricity meters (Decree No. 2210 dated December 15 2016) totaled 0.752 ths.

The amount of electricity consumed for street lighting in the city was 31288.1 ths kW/h. The average amount of electricity consumed for the operation of one luminaire was 402 kW/h.

In 2018, Miskvitlo, at the expense of the city funds, allocated for the maintenance and current repair of street lighting facilities, installed 19.2 km of street lighting networks, replaced 14.6 ths electric lamps, repaired 3.9 ths lamps, etc.

Table 1. Balance of street lighting networks in Kharkiv

| Network balance               | 2016 | 2017 | 2018 | 2019 |
|------------------------------|------|------|------|------|
| The length of street lighting networks | 2442.75 | 2498 | 2517.2 | 2523.5 |

As part of the implementation of the Comprehensive Program for Energy Saving in the city of Kharkiv for 2010–2020, 1.5 ths energy-efficient lamps were installed, the street lighting networks replaced with insulated ones, which made it possible to reduce electricity consumption.

Table 2. Street luminaires in Kharkiv

| No. | Characteristic                        | Object, recreation area, alley |
|-----|---------------------------------------|-------------------------------|
| 1   | Type of luminaire                     | ZhTU* high-pressure sodium lamps (HPS) |
| 2   | Type of light source (lamp)           | electromagnetic ballast (lighting ballast) |
| 3   | Type of ballast                       | Lamps 70                      |
| 4   | Power of one luminaire, W             | Ballast 70                    |
|     | Total                                 | 120-130                       |
| 5   | Number of luminaires per object, pcs. | 40                            |
| 6   | Luminaire installation method         | crowning                      |
| 7   | On the poles                          | metal park luminaires         |
| 8   | Number of luminaires per pole         | 1                             |
| 9   | Number of poles                       | 40                            |
| 10  | Type of arrangement of poles (luminaires) | one-sided                    |
| 11  | Distance between poles (luminaires), m| max 25                        |
| 12  | Distance from poles to the edge of the road (curb) | 0.5–1                        |
| 13  | Angle of installation of luminaires in relation to the road, deg. | 90                           |
| 14  | Height of installation of luminaires, m | 4                             |
| 15  | Width of the road, m                  | 1                             |
| 16  | Total installed power of luminaires (light sources with the ballasts), kW | 2.8                           |
| 17  | Percentage of operative luminaires    | 100%                          |
| 18  | Actual average illuminance, lx        | -                             |
| 19  | Normative average illuminance, lx     | -                             |
| 20  | Object of the municipal infrastructure | Kitliarchyn Yar               |
| 21  | Total length, km                      | 0.749                         |
| 22  | Total electricity consumed for street lighting, kW h | 366                          |
| 23  | Cost of electricity for street lighting, UAH ths | 938.15                      |

* Zh – sodium lamp type HPS; T – floor, crowning; U – for outdoor lighting
The city street lighting networks were reconstructed: 143.6 km of networks, 5.3ths luminaires and 4.4ths poles were installed.

The work performed contributed to an increase in the level of lighting in the city by providing operation of 99.3% of luminaires. As of 2019, Misksvitlo completed the installation of 6.3 km of street lighting networks, 3.2ths lamps being replaced. 371 energy-efficient lamps were installed, and the replacement of street lighting networks with insulated ones was carried out.

At the expense of the city funds, allocated for the reconstruction of street lighting networks, 27.9 km of networks, 826 luminaires and 409 poles, for the amount of UAH 12.4 mln, were installed in Kharkiv.

STREET LIGHTING FACILITIES USED TODAY

Let us consider street lighting using the example of a recreation area and alley, based on the data of Misksvitlo (Tabl. 2).

Kitliarchyn Yaris a pedestrian zone, recreational area with a spring and alleys. It can be attributed to the object class PZ traffic-free pedestrian precincts, main entrances to the territory of city-wide parks, sanatoriums; side entrances to and side alleys of exhibitions; side entrances to and central alleys of stadiums; access roads to gas stations from streets of category B. Table 3 shows the normative values for this object class.

Fig. 3 shows the light distribution in Kitliarchyn Yar. Having compared the normative and calculated values, we can see that the lighting of Kitliarchyn Yar is insufficient (Tabl. 4).

Table 3. Normative values for traffic-free pedestrian precincts

| Object class | Average horizontal illuminance, $E_{\text{aver}}$, lx, no less than | $E_{\text{min}}/E_{\text{aver}}$ ratio, no less than |
|--------------|-------------------------------------------------|-------------------------------------------------|
| Class        | Subclass | $E_{\text{min}}$, lx | $E_{\text{aver}}$, lx | $E_{\text{min}}/E_{\text{aver}}$ ratio |
| P            | PZ       | 70                 | 2.7                 | 0.27                                  |
|              |          | 150                | 5.8                 | 0.32                                  |

Table 4. Normative and calculated values for Kitliarchyn Yar

| Object class | Values obtained | Light source power, W | Average horizontal illuminance, $E_{\text{aver}}$, lx, no less than | $E_{\text{min}}/E_{\text{aver}}$ ratio, no less than |
|--------------|-----------------|-----------------------|-------------------------------------------------|-------------------------------------------------|
| Class        | Subclass        | Light source power, W | $E_{\text{aver}}$, lx, no less than | $E_{\text{min}}/E_{\text{aver}}$ ratio, no less than |
|              |                 |                       | 4                                               | 0.35                                            |
|              |                 | 70                    | 2.7                                             | 0.27                                            |
|              |                 | 150                   | 5.8                                             | 0.32                                            |
|              |                 | 150                   | 10.3                                            | 0.35                                            |

Table 5. Recommendations for improving the energy efficiency of the city pedestrian zone

| Type of luminaire | Employed | Possible options |
|-------------------|----------|------------------|
| ZhTU* high-pressure sodium lamp (HPS) | Option 1: ZhTU* high-pressure sodium lamp (HPS) | Option 2: ZhTU* high-pressure sodium lamp (HPS) | Option 3: LED |
| ZhTU* electromagnetic ballast (lighting ballast) | | | |
| Lamps 70 | 150 | 150 | Employing lighting systems using solar energy |
| Total 120-130 | 195-205 | 150 + electronic ballast efficiency | |
| One-sided | One-sided | One-sided |

* Zh – sodium lamp type HPS; T – floor, crowning; U – for outdoor lighting
Recommendations for improving lighting energy efficiency of Kitliarchyn Yar:

1. It is necessary to replace the existing light sources with more powerful ones (Fig. 4) or even replace them by lighting fixtures with a different type of light curve (the so-called Pushkin’s luminaires, resembling those used in the 19th century) (Fig. 5).

2. It is appropriate to replace electromagnetic ballasts by electronic ones (Table 5).

3. To illuminate such places as Kitliarchyn Yar, it is expedient to employ autonomous lighting systems using solar energy.

To implement the program Energy Strategy of Ukraine for the period up to 2035 “Safety, Energy Efficiency, Competitiveness”, in accordance with Directive 2012/27EU of the European Parliament and the Council of 25 October 2012 on energy efficiency, Kharkiv authorities need to ensure the introduction of energy-saving technologies in the lighting of city streets and municipal facilities.

To improve the efficiency of the street lighting system and reduce the energy consumption for its operation, measures for its reconstruction and modernization are required. For this purpose, it is essential to address the following problems:

- high level of obsolescence and physical wear and tear of system elements;
- inefficient use and high losses of electricity at the stages of transportation and consumption, due to the use of obsolete and worn-out equipment;
- suboptimal distribution of the utility capacity, which leads to ineffective use of the existing lighting system;
- low efficiency of the street lighting control system, due to the lack of electric meters and remote monitoring and control of the street lighting.

With regard to the mechanism for introducing energy efficient technologies, it is necessary to envisage the following measures:

1. Analyzing the lighting facility, identifying all factors and objects that affect the calculated data, and determining the category of the lighting facility.

2. For ensuring energy efficiency and reliability of the lighting system, when designing a new lighting facility or reconstructing an old one, it is necessary to choose equipment with high efficiency, appropriate design, which provides the necessary degree of protection against environmental factors, thermal regime, and spatial distribution of light.

3. For determining the most acceptable lighting option in terms of quantitative, qualitative and economic indicators, to carry out computer modeling of various lighting options using reliable databases of luminaires which have certificates of conformity issued by specialized measuring laboratories with equipment, the characteristics of which are checked against those of leading manufacturers of lighting products.

4. Checking the electrical and lighting characteristics of luminaires planned to be used for lighting systems, in case of the absence or doubtfulness of their quality certificate, with the receipt of a proper measurement report including the following specifications:

- luminous intensity, cd;
- luminous flux, lm;
- spectral quality of radiation, nm;
- color temperature, k;
- color rendering index;
- chromaticity coordinates;
- spatial light distribution (light intensity distribution curve), cd;
- operating voltage, V;
- operating current, A;
- power consumption, W;
- power factor (PF);
- isolux and isocandela curves;
- maximum ratio of the distance between the luminaires and the height of the luminaire installation (for street lighting facilities (LF));
- utilization factor (UF);
- effective radiation angle;
• radiation scattering angle;
• luminance limitation curves;
• values of current and voltage harmonic components;
• efficiency of the luminaire.

The results are presented in the form of test reports and photometric data files in the formats: IESNA (1995, 2002), Eulumdat, CIE, CEN, CIBSE, TM14.

All tests of luminaires should be carried out in certified laboratories.

5. Applying energy-saving types of light sources.
It is necessary to replace old lighting facilities, which have already exhausted their life span, with new ones with energy-saving light sources (replace CFLs by LEDs), to use automatic control systems, which will help reduce energy costs by 60%.

6. Replacing electromagnetic ballasts with electronic ones.

The employment of electronic ballasts, e.g., in case of using HPS 250 lamps, allows to save approximately 255 kWh/year. Considering that the price per kW of electric energy is UAH 2.68, one luminaire helps save the amount of UAH 683.4 per year.

7. To light areas where there is a lot of space, autonomous lighting systems using solar energy can be employed.

For achieving a greater economic effect of the use of autonomous lighting systems, it is necessary to design such a system for a particular lighting facility to meet lighting standards.

8. Autonomous lighting systems can be used to illuminate main streets, park areas with stations for recharging electric cars, electric scooters and other types of electric vehicles.

9. Implementing remote control and monitoring systems for street lighting.

In general, with the introduction of energy-saving technologies in lighting, it is possible to save 79.33 ml. kWh of electricity, while burning by 10.42 ml. m³ of natural gas less than before.

CONCLUSIONS

Well-lit streets in the dark increase the productivity of the visual system and significantly reduce the number of accidents. To improve the efficiency of the street lighting system and reduce the energy consumption for its operation, measures for its reconstruction and modernization are required.

It is necessary to replace old lighting facilities, with new ones with energy-saving light sources, to use automatic control systems, which will help reduce energy costs by 60%. Replacing electromagnetic ballasts with electronic ones.

DISCLOSURE STATEMENT

No potential conflict of interest was reported by the author(s).

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**Anotatsiia.** Якісне зовнішнє освітлення покращує візуальне сприйняття дороги та значно зменшує кількість дорожньо-транспортних пригод. Встановлено, що загальна кількість ДТП може бути зменшена на 30% для доріг загального користування та на 45% для особливо небезпечних зон (наприклад перехрестя). Подвоєння середньої якості освітлення може зменшити кількість ДТП на 30% для доріг загального користування та на 45% для особливо небезпечних зон. Згідно з науковими дослідженнями, освітлення дорог в ночное время у більшості випадкових ситуацій сприяє зниженню кількості ДТП на 30%, а iі випадках з 45%.
ньої яскравості дорожнього покриття значно зменшує кількість ДТП у темряві та сутінках. Достатньо вуличне освітлення сприяє скороченню споживання електроенергії (зниження експлуатаційних витрат); покращення екологічної ситуації; сприянню бізнесу, туризму та інвестиційній діяльності; зменшенню кількості кримінальних правопорушень. Аналіз останніх досліджень та публікацій допоміг обрати найкращі європейські практики, які можна використати для покращення зовнішнього освітлення в Україні. Мережа вуличного освітлення носійно зростає та модернізується. Для освітлення міста в мережі використовуються різні види джерел світла. Сьогодні підтримують лампи високого тиску (ДНаТ), які все частіше замінюються світлодіодними джерелами світла. Немала частка припадає на метало-галогенні лампи. Найменша кількість джерел світла в системі зовнішнього освітлення є ртути високого тиску та компактних люмінесцентних ламп (КЛЛ). Для підвищення ефективності системи вуличного освітлення йї функціонування та зменшення споживання енергії необхідні заходи щодо її реконструкції та модернізації. Для цього необхідно вирішити такі проблеми: високий рівень застарілості та фізичного зносу елементів системи; неефективне використання та великий втрати електроенергії на етапах транспортування та споживання, через використання застарілого та зношеного обладнання; неоптимальний розподіл потужності комунального підприємства, що призводить до неефективного використання існуючої системи освітлення; низька ефективність системи управління вуличним освітленням, через відсутність електролічильників та дистанційного контролю та управління вуличним освітленням. Впровадження енергозберігаючих видів джерел світла один із шляхів модернізації існуючої системи зовнішнього освітлення. Необхідно замінити старі освітлювальні прилади, які вже вичерпали свій термін служби, на нові енергозберігаючі джерела світла (замінити КЛП на світлодіоди), використовувати автоматичні системи управління. Все це в свою чергу допоможе знизити витрати на енергію на 60%. Для підвищення енергоефективності системи зовнішнього освітлення також рекомендується проводити заміну електромагнітних баластів на електронні. Використання електронних баластів, на приклад, у разі використання ламп ДНаТ 250, дозволяє заощадити приблизно 255 кВт год/рік. Враховуючи, що ціна за кВт електричної енергії становить 2,68 грн., один світильник допомагає заощадити суму 683,4 грн. на рік.

Ключові слова: зовнішне освітлення, енергозбереження, джерела світла, пускорегулююча апаратура, системи керування.

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