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Energy Efficiency of the Road Lighting: The Impact of Active Power Losses on Energy Performance Indicators and Electricity Costs

Roman Sikora and Przemysław Markiewicz

Abstract

Improving the energy efficiency of road lighting is currently one of the most important issues. One of the methods of improving energy efficiency is the use of dimmable luminaires. In order to be able to compare the energy efficiency of different technical solutions, EN 13201-5 introduces energy performance indicators for road lighting installations. The chapter describes energy performance indicators for road installation and the impact of active power losses on these indicators and electricity costs. In order to accurately calculate the above indicators, the active power losses in the elements of the lighting installation should be taken into account. The chapter presents the dependencies which can be used to calculate the active power losses in single- and three-phase systems. In addition, an example of calculation of energy performance indicators, active power and energy losses and electricity costs is provided. The calculation was made for an exemplary installation of road lighting with dimmable luminaires. The analysis was done for single-phase and three-phase installations.

Keywords: road lighting, energy performance indicators, cost of electricity consumption, LED luminaire, active power losses, EN 13201

1. Introduction

Road lighting is one of the basic elements of a road infrastructure. Proper lighting of the road (also in conflict zones with an intersection of pedestrian and motor traffic as well as in zones intended for pedestrian traffic, cycling and slow-moving vehicles) is an important element of road safety. Quantitative and qualitative lighting requirements for areas and road zones are characterised by a lighting class. The requirements for road lighting apply only to night hours. They may be subject to change at different times of the night and in different seasons. The EN 13201 [1–5] standards allow the use of different lighting classes for particular time periods of the lighting operation, e.g., depending on the traffic volume. Lowering the lighting class means reducing the requirements for lighting parameters such as

luminance (or illuminance), longitudinal and overall uniformity and threshold increment. It is therefore possible to reduce the luminous flux of the luminaire by reducing the luminaire's power.

The luminous flux of the luminaires can be changed step by step or smoothly over a wide range. However, the depth of the reduction of the luminous flux should be limited to the level at which the requirements of EN 13201 [1–5] are fulfilled. The highest possible energy savings must not deteriorate road safety. The literature describes a number of solutions for power regulation in lighting installations [6–11]. Lighting control systems can be divided into two groups. The first group concerns the use of individual controllers equipped with astronomical clocks in the luminaires, which automatically adjust the lighting time to sunrise and sunset, implementing the most frequently set work schedules. The use of additional sensors responding to natural light, traffic, etc. increases the functionality of the lighting installation by reacting dynamically to changing surrounding conditions. The second group concerns a central controller that supports a group of luminaires or individual circuits, which is installed, e.g., in a lighting switchboard. It can also be an IT system that is part of the Smart City system, centrally managing lighting installations [11–14]. The main aim of power reduction is to improve the energy efficiency of road lighting [15–20]. This is equivalent to decreasing the electric energy consumption and CO₂ emissions [15]. It should be remembered that the overall aim of road lighting is to ensure road safety, not to obtain maximum energy savings.

The flow of current through the elements of the mains causes power and energy losses. Losses of power and energy may indicate financial and technical losses. Financial losses are understood as an increase of operational costs and technical losses as an increase of electricity consumption [12, 20–24]. Power losses in road lighting installations depend, among other things, on the network system (single-phase, three-phase network), the complexity of the network (number of circuits and lighting luminaires) and the used power supply devices. In the case of road lighting installations, power losses occur primarily in such elements as supply cables (wires) and protection and control devices [25, 26]. When calculating the electricity consumption during the design phase of a lighting installation, power losses are often omitted. This results in an undervaluation of electricity costs compared to real consumption. Analyses of energy efficiency and operating costs of lighting installations usually neglect the aspects of reactive power [27]. The first one is related to the occurrence of active power losses due to the reactive power flow. The second aspect concerns the dependence of the reactive power of the luminaire on the power and/or control conditions. The level of losses also depends on the occurrence of higher harmonics of the supply current [28–33]. The increasingly common use of dimmable luminaires, especially LED luminaires, in road lighting means that energy consumption and energy losses depend on the lighting time and the level of luminaire power reduction. Previously, energy consumption and power losses were calculated on the assumption that the luminaire consumes constant power. During the measurements of dimmable LED luminaires, a strong dependence of the power factor (reactive power) was observed, along with an increase of the higher harmonic values at the change of the level of control. Calculations of active power losses and energy consumption should be carried out for the assumed lighting schedule.

The chapter presents the method of calculating active power losses, energy performance indicators and electricity costs in road lighting installations. The described method may be used for analysis of installations with dimmable luminaires. The usefulness of the method is presented on the example of the analysis of road lighting installation with dimmable luminaires.

2. Energy performance indicators according to EN 13201-5 standard

The EN 13201-5 [5] standard defines two energy efficiency indicators for road lighting: the power density indicator (PDI) D_P and the annual energy consumption indicator (AECI) D_E . These indicators can be used to estimate the potential savings achieved by improving energy performance and reducing the environmental impact of road lighting. The defined PDI and AECI indicators are used to compare the energy performance of different variants of road lighting design. The comparison of the energy performance indicators for the different design variants of the road lighting installation is possible with the assumption of identical installation geometry. This is a limitation of the use of PDI and AECI indicators. These indicators can be applied to all traffic areas (lighting classes M, C and P). The power density indicator (PDI) D_P determines the amount of energy needed to provide adequate road lighting in accordance with the applicable EN 13201-1 [1] and EN 13201-2 [2] standards. It is calculated as the quotient of the P power of the lighting installation and the sum of the products of the average lighting intensity on the horizontal plane of the area to be lit Eq. (1):

$$D_P = \frac{P}{\sum_{i=1}^n (E_i^{ah} \cdot A_i)} \quad (1)$$

According to EN 13201-2 [2], it is possible to reduce the lighting requirements of a road during a period of reduced traffic, i.e., to change the lighting class of a road, e.g., from M3 to M4. In this case, the power density indicator shall be calculated individually for road classes M3 and M4.

The annual energy consumption indicator (AECI) D_E determines the annual electricity consumption during the year. Its value is calculated as follows Eq. (2):

$$D_E = \frac{\sum_{j=1}^m (P_j \cdot t_j)}{A} \quad (2)$$

EN 13201-5 [5] standard recommends the use of PDI and AECI together. The best variant of road lighting is when both of these indicators have minimum values.

The system power P should be calculated as the sum of all the equipment necessary to light the road or road section. System power P is defined as

$$P = \sum_{k=1}^{n_p} P_k + P_{ad} \quad (3)$$

In the case of dimmable luminaires according to EN 13201-5 [5], the power reduction factor k_{redP} can be introduced. The power reduction factor k_{redP} determines the degree of luminaire dimming. It accepts values from 0 to 1. For a reduction factor of $k_{redP} = 1$, the luminaire is set to the maximum level (100%) and operates at maximum power and maximum luminous flux. The standard recommends the adoption of a reduction factor for the system power of the whole lighting installation. This is not entirely correct, because the power of the P_{ad} additional devices may not change as the dimming level of luminaire changes or may change in any other way. A second reduction factor may therefore be introduced to take into account changes of additional equipment power with function of dimming change k_{red}^{ad} . It can take values from 0 to 1. Therefore, the power of the lighting installation for the j^{th} period of operation can be calculated as

$$P = \sum_{k=1}^{n_{lp}} k_{redP} P_k + k_{red}^{ad} P_{ad} \quad (4)$$

Estimating the P_{ad} power during the design process of road lighting can be difficult. Therefore, usually at the design stage, this power is omitted in the calculations. This may cause the calculated energy performance indicators to be underestimated. In order to illustrate this, consider the following example.

2.1 Example

The road lighting installation consists of 10 luminaires with a power of $P = 50$ W. Due to the possibility of lowering the lighting class of the road, the luminaire power (luminous flux) can be reduced by 50% ($k_{redP} = 0.5$). It is assumed that the P_{ad} power is 5% of the installed luminaire power at 100% of dimming. It does not change with the dimming change.

Total luminaire power at 100% of dimming is equal to

$$P_{inst} = \sum_{j=1}^{10} k_{redP} P_{lum} = 10 \cdot 1 \cdot 50 = 500 \text{ W}$$

Calculated value of the P_{ad} power is equal to

$$P_{ad} = 0.05 \cdot P = 0.05 \cdot 500 = 25 \text{ W}$$

Total system power value at 100% of dimming

$$P = P_{inst} + P_{ad} = 500 + 25 = 525 \text{ W}$$

Total luminaire power at 50% of dimming is equal to

$$P_{inst}^{red} = \sum_{j=1}^{10} k_{redP} P_{lum} = 10 \cdot 0.5 \cdot 50 = 250 \text{ W}$$

Total system power value at 50% of dimming

$$P^{red} = P_{inst}^{red} + P_{ad} = 250 + 25 = 275 \text{ W}$$

So

$$\frac{P_{ad}}{P_{inst}^{red}} = \frac{25}{275} = 9.09\%$$

Power P_{ad} is in this case 9.09% of the total system power and should not be omitted.

3. Calculation of active power losses in road lighting installation

Typical installation of road lighting consists of the following elements:

- Cable protection located in the lighting switchboard
- Relay placed in the lighting switchboard

- Cable (wire)
- Protection in the pole (placed in the pole switchboard)
- Wire connecting the pole switchboard with luminaire

In each of the listed elements of the installation, an active power loss occurs. The total active power losses ΔP_{Σ} in the road lighting system are the sum of power losses in its individual elements. Road lighting installations can be single-phase or three-phase. The method of calculating losses in these types of installations is similar but not identical.

For three-phase installation, the total active power losses should be calculated by dependence Eq. (5):

$$\Delta P_{\Sigma}^{3P} = \Delta P_C^{3P} + \Delta P_N + \Delta P_W + \Delta P_{PPB} + \Delta P_{PP} + \Delta P_R \quad (5)$$

The active power losses in the neutral conductor of the power cable should be taken into account. They are caused by the flow of higher harmonics of the zero sequence and being a multiple of the number 3.

The total power losses of the single-phase lighting installation ΔP_{Σ}^{1P} can be calculated as

$$\Delta P_{\Sigma}^{1P} = \Delta P_C^{1P} + \Delta P_W + \Delta P_{PPB} + \Delta P_{PP} + \Delta P_R \quad (6)$$

For single-phase installations, losses in the neutral conductor are included in ΔP_C^{1P} .

For three-phase lighting installation, power losses in the cable can be determined from the relationship [34]:

$$\Delta P_C^{3P} = \frac{3l}{\gamma_C S_C} \left[n^2 \left(\frac{l_{01} + l}{l} \right) + \frac{n(n-1)(2n-1)}{2} \right] I_{Lum}^2 \quad (7)$$

The active power losses in a cable in a single-phase installation are calculated from Formula (8) [34]:

$$\Delta P_C^{1P} = \frac{2l}{\gamma_C S_C} \left[n^2 \left(\frac{l_{01}}{l} \right) + \frac{n(n-1)(2n-1)}{6} \right] I_{Lum}^2 \quad (8)$$

The active power losses in the neutral conductor are calculated as [34]

$$\Delta P_N = \frac{l}{\gamma_C S_C} \left[9n^2 + \frac{l_{01}}{l} + \frac{n(3n-1)(6n-1)}{2} \right] \sum_{h=3}^{\infty} I_{hLum}^2 \quad (9)$$

or

$$\Delta P_N = \frac{l}{\gamma_C S_C} \left[9n^2 + \frac{l_{01}}{l} + \frac{n(3n-1)(6n-1)}{2} \right] I_{NLum}^2 \quad (10)$$

Power losses in the wire connecting the pole switchboard and luminaire are calculated by using Eq. (11):

$$\Delta P_W = 2I_{Lum}^2 R_{PW} = \frac{2l_{PW}}{\gamma_{PW} S_{PW}} I_{Lum}^2 \quad (11)$$

Power losses in protection in the lighting switchboard are determined by the following dependence:

$$\Delta P_{PPB} = 3I_{LI}^2 R_{PPB} \quad (12)$$

In the case when the protection is realised by miniature circuit breaker (MCB)

$$R_{PPB} = R_{MCB} \quad (13)$$

Knowing the rated active power losses of the minimal circuit breaker ΔP_{MCB} is given for its rated current. R_{MCB} can be determined by

$$R_{MCB} = \frac{\Delta P_{MCB}}{3I_{MCB}^2} \quad (14)$$

The resistance of the whole protection device, if used for protection is a fuse to protect the cable, is the sum of the resistance of the fuse and the fuse carrier Eq. (15):

$$R_{PPB} = R_{PBFB} + R_{PBF} \quad (15)$$

Resistance of fuse carrier can be determined from Eq. (16), and resistance of fuse is calculated as Eq. (17)

$$R_{PBFB} = \frac{\Delta P_{PBFB}}{I_{PBFB}^2} \quad (16)$$

$$R_{PBF} = \frac{\Delta P_{PBF}}{I_{PBF}^2} \quad (17)$$

The active power losses in the protection device in the pole switchboard are calculated from Eq. (18)

$$\Delta P_{PP} = 3I_{Lum}^2 R_{PP} \quad (18)$$

If a miniature circuit breaker (MCB) is used, the R_{PP} resistance is equal to R_{MCB} :

$$R_{PP} = R_{MCB} \quad (19)$$

If a fuse is used to protect the wire in the pole, the resistance of the whole protection device is calculated as the sum of the resistance of the fuse and the fuse carrier (Formula (15) can be used).

A relay is usually used to switch on and off the lighting circuit. The active power losses of relay are calculated as

$$\Delta P_R = I_{LI}^2 R_R \quad (20)$$

The relay resistance R_R can be calculated as the quotient of the rated active power losses of the ΔP_{RR} relay (given for rated current) and the square of the rated current Eq. (21):

$$R_R = \frac{\Delta P_{RR}}{I_R^2} \quad (21)$$

The number of light points is equivalent to the number of poles, since it is assumed that the luminaires are mounted on poles individually.

4. Calculation of active energy losses in road lighting installation

In the case of road lighting installations (circuit) with luminaires without dimming (without power reduction), the active energy consumed by the circuit (installation) E_T is equal to the product of active power of lighting circuit (installation) P and lighting time t_{use} , according to the relation (22):

$$E_T = P \cdot t_{use} \quad (22)$$

For the road lighting installations with dimmable luminaires operating according to a fixed work schedule, the active energy consumed by the lighting circuit (installation) is the sum of the energy consumed at each power reduction level. It was assumed that the luminaires used in the circuit are of the same rated power and they operate according to the same daily work schedule. The active energy of the circuit is calculated as the sum of the energy absorbed at each reduction level and the number of luminaires in the n_{lu} circuit (installation), according to the relation (23):

$$E_T = P_k \cdot n_{lu} \cdot \sum_{i=1}^{n_{dim}} k_{redP_i} \cdot t_{use_i} \quad (23)$$

The active energy flow in the system causes active energy losses, calculated on the basis of dependence (24):

$$E_{\Delta P} = \Delta P_{\Sigma} \cdot t_{use} \quad (24)$$

The total active energy losses for the n_{dim} levels of luminaire control in the daily cycle can be calculated from the dependence (25):

$$E_{\Delta P} = \sum_{i=1}^{n_{dim}} \Delta P_{\Sigma_i} \cdot t_{use_i} \quad (25)$$

Taking into account the power reduction factor k_{redP} for each level of dimming, obtain the dependence (26) for the total losses of active energy in the lighting circuit:

$$E_{\Delta P} = \Delta P_{\Sigma} \sum_{i=1}^{n_{dim}} k_{redP_i} \cdot t_{use_i} \quad (26)$$

These dependencies assume a constant number of luminaires in the circuits and a certain length of the power line. The total active energy collected by the lighting installation is the sum of the energy taken from the luminaires, the active energy losses and energy of auxiliary devices E_{ad} in the lighting components (29). The definition given in the standard [5] regarding P_{ad} power is too long; the authors decided to introduce the concept of auxiliary devices of lighting installation. The P_{ad} power can be defined as the sum of the auxiliary devices' power. Therefore, the power of the P_{ad} can be calculated from the following equation:

$$P_{ad} = \sum_{p=1}^w \sum_{d=1}^{n_d} P_{ad,d,p} \cdot k_{red,d,p}^{ad} \quad (27)$$

Each auxiliary device has a different rated output marked as $P_{ad,d,p}$. The n_d variable means the number of periods of power reduction of individual auxiliary

devices. There are w auxiliary devices in the installation that must be taken into account in the calculation.

The energy E_{ad} is calculated as the sum of the energy of all auxiliary devices necessary for the operation of the installation (28):

$$E_{ad} = \sum_{p=1}^w \sum_{d=1}^{n_d} P_{ad_{d,p}} \cdot k_{red_{d,p}}^{ad} \cdot t_{use_{d,p}}^{ad} \quad (28)$$

The t_{use}^{ad} variable in Formula (28) means the operating times of the individual auxiliary devices. When calculating the energy E_{ad} , it is not correct to take the same working time of all auxiliary devices. Each of these devices can work differently compared to the light schedule:

$$E_{\Sigma LI} = E_T + E_{\Delta P} + E_{ad} \quad (29)$$

After the transformation, a dependency Eq. (30) is obtained:

$$E_{\Sigma LI} = P \cdot \sum_{i=1}^{n_{dim}} k_{red P_i} \cdot t_{use_i} + \Delta P_{\Sigma} \cdot \sum_{i=1}^{n_{dim}} k_{red P_i} \cdot t_{use_i} + \sum_{p=1}^w \sum_{d=1}^{n_d} P_{ad_{d,p}} \cdot k_{red_{d,p}}^{ad} \cdot t_{use_{d,p}}^{ad} \quad (30)$$

5. Calculation example

5.1 Electrical and photometric parameters of a dimmable LED road luminaire

To estimate the energy efficiency of a lighting installation, it is necessary to know the electrical and photometric parameters of the luminaires. The parameters of all devices included in the installation should also be known i.e.: the types, cross-sections and lengths of wires or cables, types of applied protection and control devices. These data are usually available in catalogues. In the case of dimmable luminaires, the dimming characteristics are not always presented in the catalogue. Dimming characteristics are understood as the dependence of electrical and photometric parameters of the luminaire on dimming. This also applies to files with photometric data in the *eulumdat* format. Manufacturers should provide photometric data for different dimming or give reduction coefficients better in the form of mathematical dependence. This will ensure adequate accuracy of calculations and will facilitate the work of the designer. If this data is unavailable, then having a sample of the luminaire, the best solution is to take measurements of electrical and photometric parameters. In this way, the characteristics of the dimming for the given regulation range can be achieved.

In order to illustrate the presented method, the calculation results for an example of a road lighting installation with dimmable luminaires are presented. Energy performance indicators according to [5], electricity consumption and costs have been calculated for the following variants:

- Without taking into account active power losses
- Taking into account the active power losses for a three-phase installation
- Taking into account the active power losses for a single-phase installation

When power losses are omitted, the results of calculations are identical for both types of installations (single- and three-phase). In calculations, active power losses in all previously mentioned (Section 3) elements of the installation were taken into account. The LED dimmable luminaire with a rated power of 140 W was selected for the analysis. Implemented luminaire control enabled regulation from 10 to 100% of rated power. The manufacturer did not specify the exact power values and luminous flux of the luminaire for particular levels of dimming. Measurements were taken in the full control range with a step of 10%, and the results are summarised in **Table 1**. The dimming levels have been adopted in accordance with the manufacturer's assumption, which apparently does not correspond to the percentage of the luminaire's power or its luminous flux.

To measure the electrical parameters of the luminaire, the FLUKE 1760 power quality analyser was used. The luminous flux was measured in an Ulbricht sphere with a diameter of 2 m and with the use of the SONOPAN L-100 lux metre. The Agilent 6834B power supply was used to supply the luminaire. The luminaire was powered by an undeformed (purely sinusoidal) rated voltage of RMS 230VAC.

Analysing the results of **Table 1**, it can be seen that 10% of the dimming actually corresponds to about 26% of the luminaire's power and about 33% of the luminous flux. It can be assumed that both the active power of the luminaire and its luminous flux change approximately linearly. Analysing changes in reactive power, it is stated that its changes compared to active power are much smaller. At 10% of the dimming, reactive power reaches 79% of the initial value. This causes the power factor to decrease to 0.78 for 10% of the dimming level. It corresponds to the value of $\text{tg}\varphi = 0.81$. In many countries, the permissible reactive power level will be exceeded. It should be emphasised that the luminaire has the capacitive character of the power factor.

Disturbances generated to the power supply network by LED luminaires are the results of a pulse switching technique used in the power supplies. Modern impulse power supplies are equipped with circuits limiting the emission of higher harmonics of current and PFC systems. Most often, these systems are designed for the case of the power supply under 100% of load. This usually results in an increase in the level of higher current harmonics for lower dimming levels, which causes an increase of THD_I . For the tested power supply, the THD_I value increased from 8% for 100% of

Dimming (%)	P_{lum} (W)	$P_{lum}^{\%}$ (%)	Q_{lum} (var)	$Q_{lum}^{\%}$ (%)	PF_D (–)	PF_{DD} (–)	$\text{tg}\varphi$ (–)	THD_I (%)	Φ_{lum} (lm)	$\Phi_{lum}^{\%}$ (%)
10	37.71	26.47	30.64	71.91	0.78	0.76	0.81	21.05	4579	32.52
20	49.62	34.82	32.73	76.81	0.84	0.82	0.66	16.84	5859	41.61
30	65.33	45.85	35.25	82.73	0.88	0.87	0.54	14.34	7437	52.82
40	79.27	55.63	35.95	84.37	0.91	0.90	0.45	12.34	8804	62.52
50	91.87	64.47	37.91	88.97	0.92	0.92	0.41	11.01	9971	70.81
60	103.50	72.64	39.72	93.22	0.93	0.93	0.38	10.42	10,980	77.98
70	114.22	80.16	40.81	95.78	0.94	0.94	0.36	9.82	11,870	84.30
80	124.22	87.18	41.37	97.09	0.95	0.95	0.33	9.15	12,664	89.94
90	133.56	93.73	41.86	98.24	0.95	0.95	0.31	8.45	13,390	95.09
100	142.49	100.00	42.61	100.00	0.96	0.96	0.30	8.00	14,081	100.00

Table 1.
The values of electrical and photometric parameters of LED 140 W luminaires for different levels of dimming.

the dimming to 21% for 10% of dimming. This is a change of 163%. This is also the reason for the change in the power factor of the luminaire.

In order to calculate lighting parameters on the road, it is necessary to know the light distribution curves for a given dimming. The *eulumdat* files with photometric data for a given dimming were not available for the analysed luminaire. Therefore, photometric measurements were taken for the whole dimming range (in 10% increments). Based on the measurement results, the photometric files, *eulumdat*, were developed. **Figure 1** presents the light distribution curves for the selected luminaire in a C- γ coordinate system for 100% of dimming.

5.2 Parameters of lighting installation

The following assumptions were made for the calculations:

- The installation is made of copper cable with a cross-section of $4 \times 16 \text{ mm}^2$.
- For copper, the specific conductivity value of $56 \text{ m}/\Omega \text{ mm}^2$ has been assumed.
- The pole wire from the pole switchboard to the luminaire is a copper wire with a cross-section of 1.5 mm^2 and length = 10 m.
- The protection of the lighting circuit is a gG (gL)-type fuse with a rated current of 25 A together with a three-phase fuse carrier with a rated current of 160 A. The catalogued active power losses for the rated current are 12 and 2.4 W, respectively.
- For single-phase installation, the following were assumed: gG (gL)-type fuse with a rated current of 25 A and active power losses equal to 2.4W and catalogued active power losses of single-phase fuse carrier 2.6W with a rated current of 160 A.
- The lighting circuit is switched on by a three-phase relay with a rated current of 25 A, whose catalogue power losses for the rated current are 7.9 W and for single-phase catalogue power losses equal to 4.4 W and the rated current is 25 A.

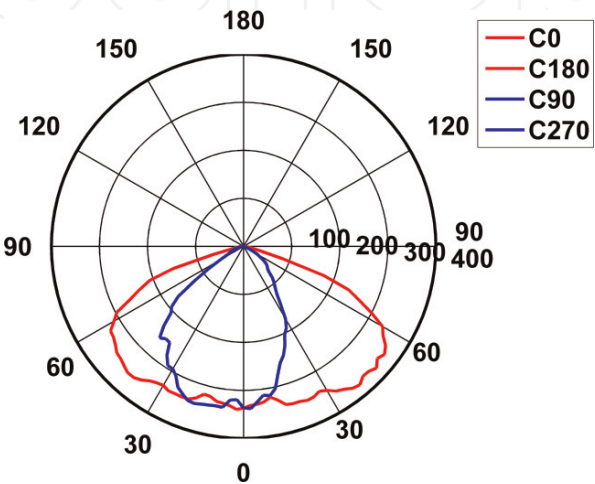


Figure 1.
Light distribution curves for the selected luminaire in a C- γ coordinate system.

- As a protection in the pole, a gG (gL)-type fuse with a rated current of 6 A was used together with a one-phase fuse carrier with a rated current of 16 A. Power losses for the rated current read from the manufacturer's catalogue are, respectively, 1.7 W for the fuse and 3 W for the fuse carrier.
- The calculation was made for an installation of road lighting consisting of 30 points of light (single- and three-phase).
- The luminaires are mounted individually on the poles, i.e., the number of light points (poles) is equal to the number of luminaires.

In order to calculate the energy efficiency performance indicators, the lighting system project must be done. The list of assumed parameters of the lighting installation of the analysed road is presented in **Table 2**.

5.3 Results of the calculations of power and energy losses

The results of calculations of lighting parameters for the analysed road are shown in **Table 3**. They have been made for the full range of luminous flux adjustment. On the road, the lighting class M3 was established. The calculations were performed in the DIALux® programme. The symbol O1 or O2 indicates the results for the observer 1 and 2, respectively.

The power of the P_{ad} has been omitted from the calculations ($P_{ad} = 0$). For dimming levels from 90 to 60%, the lighting requirements for one class lower than for full dimming are met (M4). Two lighting classes below the assumed value are met for dimming range 30–50% (M5).

The values of the power density indicator are determined from Formula (1).

Table 4 presents the calculated values of the active power losses and in **Table 5** the calculated values of power density indicator D_P . The impact of power losses on PDI is noticeable. The value of PDI in the calculation increases when active power losses are taken into account. The increase in PDI is equal to the percentage of the active power losses in relation to the total power of the lighting system. Decreasing the dimming level reduces the value of the indicator D_P . Due to linear changes in active power and light intensity in dimming, PDI value changes do not correspond to a dimming change. From the point of view of improving the energy efficiency of

Parameter	Value
Arrangements	Single row, bottom
Pole distance (m)	35
Height (m)	9.5
Inclination (°)	5
Pole distance from roadway (m)	0.65
Boom length (m)	0.5
Number of poles	30
Street width (m)	7
Maintenance factor	0.80

Table 2.
Parameters of road lighting installations.

Dimming (%)	L_{avg}		U_o		U_I		f_{TI}		Lighting class
	(cd m ⁻²)		(%)		(%)		(%)		
	O1	O2	O1	O2	O1	O2	O1	O2	
100	1.02	1.09	0.51	0.50	0.74	0.84	8	6	M3
90	0.97	1.04					8	6	M4
80	0.91	0.98					8	6	M4
70	0.85	0.92					8	6	M4
60	0.79	0.85					7	6	M4
50	0.72	0.78					7	6	M5
40	0.64	0.69					7	5	M5
30	0.54	0.58					7	5	M5
20	0.43	0.46					7	5	M6
10	0.34	0.36					6	5	M6

Table 3.
Calculated lighting parameters.

Dimming (%)	P	ΔP_{3P}	ΔP_{1P}	$P + \Delta P_{3P}$	$P + \Delta P_{1P}$
	(W)	(W)	(W)	(W)	(W)
100	4334.10	55.76	320.02	4389.86	4654.12
90	4081.20	49.12	281.85	4130.32	4363.05
80	3806.70	42.95	246.09	3849.65	4052.79
70	3503.70	37.22	212.77	3540.92	3716.47
60	3178.20	30.62	174.52	3208.82	3352.72
50	2824.50	24.66	140.05	2849.16	2964.55
40	2433.90	19.50	109.38	2454.40	2543.28
30	2016.90	14.88	82.49	2031.78	2099.39
20	1531.50	9.44	51.20	1540.94	1582.70
10	1165.20	7.01	36.66	1171.21	1201.86

Table 4.
The calculated values of active power losses for three- and single-phase installation.

the installation is beneficial. A significant limitation in the level of the assumed reduction in the power of the installation is to meet the lighting requirements. The highest total active power losses in three-phase installation occur for luminaires with a full level of control (100%), and they amount to 55.76 W. By reducing the power of the luminaire, these losses decrease and are equal to only 7.01 W. For a single-phase installation, the level of losses and their contribution to the overall power balance is significantly higher. Analysing the percentages of active power losses in particular elements of the lighting installation, it is stated that the largest share of losses (regardless of the level of dimming) occurs in the power cable.

The AECI indicator value can be calculated if the light schedule is known. The luminaires can operate at 100% light output, or at set hours, it can be reduced. It was assumed that the moment of switching on and off the installation is determined on the basis of astronomical tables. For simplicity it was assumed that the same time

of switching on and off the installation is the same for each day of the month. From 16.00 to 19.00 and from 5.00 to 7.00, the luminaires work with 100% of dimming. Between 23.00 and 4.00, the luminaires work with 60% of dimming. During reduced traffic hours, it is possible to lower the lighting class from M3 to M4. Based on **Table 3**, for 60% of dimming the lighting requirements for class M4 are met. The adopted lighting schedule is the result of this. A graphical presentation of the lighting schedule is shown in **Figure 2**. The time moments marked as t_{on} and t_{off} on **Figure 2** indicate the time of switching on and off the lighting system. These times are different for each month of the year.

Table 6 presents the calculation results of AECI indicator (D_E) for all cases considered. The calculation is based on the assumption that the installation operates with two dimming levels (marked as D1 and D2). Similarly to the D_p indicator, lowering the dimming causes lowering its value.

Dimming (%)	E^{ah}	D_p	D^{3P}_p	D^{1P}_p
	(lx)	(mW lx ⁻¹ m ⁻²)	(mW lx ⁻¹ m ⁻²)	(mW lx ⁻¹ m ⁻²)
100	19.00	32.11	32.52	34.48
90	18.00	31.92	32.30	34.12
80	17.00	31.52	31.87	33.55
70	16.00	30.82	31.15	32.69
60	15.00	29.82	30.11	31.46
50	14.00	28.40	28.64	29.80
40	12.00	28.55	28.79	29.83
30	10.00	28.39	28.60	29.55
20	8.01	26.91	27.08	27.81
10	6.29	26.07	26.23	26.89

Table 5.
The calculated values of the energy performance indicators for three- and single-phase installation and horizontal average illumination.

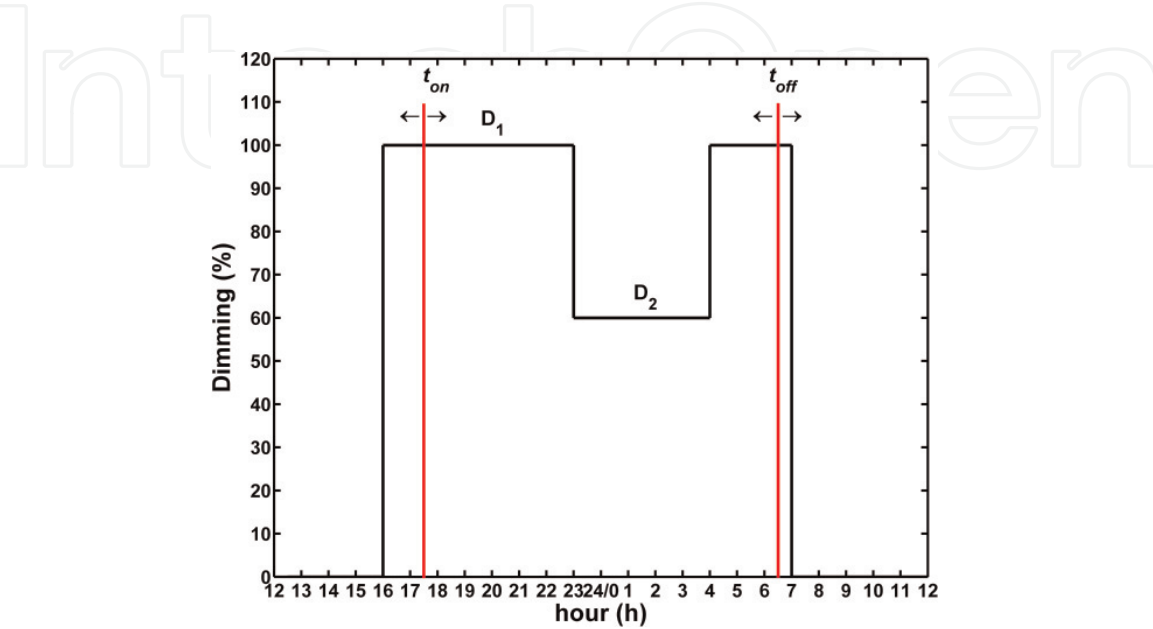


Figure 2.
Installation lighting schedule accepted for calculation.

The value of the AECI without dimming is 2.41 (kWh m⁻²) for installations without losses. For a lighting installation operating with the assumed lighting schedule, lowering the D2 dimming level to 10% causes a decrease in the AECI value to 1.60 (kWh m⁻²) when energy losses are not taken into account. The greatest influence on the AECI value is the dimming value and lighting time with reduced luminous flux.

Table 6 shows the results of the calculation of the active energy consumed by lighting installations without dimming. The calculations are for single- and

	D_E	D^{3P}_E	D^{1P}_E
	(kWh m ⁻²)	(kWh m ⁻²)	(kWh m ⁻²)
Without dimming	2.41	2.44	2.59
D1 = 100%, D2 = 90%	2.34	2.37	2.51
D1 = 100%, D2 = 80%	2.27	2.30	2.43
D1 = 100%, D2 = 70%	2.20	2.22	2.35
D1 = 100%, D2 = 60%	2.11	2.14	2.25
D1 = 100%, D2 = 50%	2.02	2.04	2.15
D1 = 100%, D2 = 40%	1.78	1.79	1.88
D1 = 100%, D2 = 30%	1.81	1.83	1.93
D1 = 100%, D2 = 20%	1.69	1.71	1.80
D1 = 100%, D2 = 10%	1.60	1.61	1.70

Table 6.
Summary of the calculated values of the annual energy consumption D_E indicators without and including losses for single- and three-phase installation.

Month	LED without dimming				
	E_T	E^{3P}_T	E^{1P}_T	$E^{3P}_{\Delta P}$	$E^{1P}_{\Delta P}$
	(kWh)	(kWh)	(kWh)	(kWh)	(kWh)
January	2015	2041	2164	26	149
February	1578	1598	1694	20	116
March	1478	1497	1587	19	109
April	1170	1185	1257	15	86
May	941	953	1010	12	69
June	910	922	977	11	67
July	941	953	1010	12	69
August	1209	1225	1299	15	89
September	1430	1449	1536	18	106
October	1612	1633	1731	21	119
November	1820	1844	1955	23	134
December	2015	2041	2164	26	149
Annual	17,120	17,340	18,384	220	1264

Table 7.
Summary of the calculated values of energy consumption by lighting installation without and including losses without dimming.

three-phase installations with and without active power losses. **Table 7** presents the calculation results of the consumed active energy for the installation working with the assumed lighting schedule. **Figures 3–5** show the calculated amounts of electricity consumed in the analysed variants by lighting installation on a month-per-month scale.

The annual active energy consumption for the considered lighting installation without control is 17,120 kWh. In the case of operation of road lighting installation with the assumed schedule, the annual energy consumption is reduced to 15,010 kWh. This is a decrease of 12%. The highest energy consumption as well as energy losses occurs in the winter months, in December and January. The highest electricity consumption equals 2015 kWh. The lowest consumption is noted in June and equals only 910 kWh for the analysed lighting system. For an installation without dimming, the inclusion of active power losses has resulted in a 1.28% increase of the calculated annual energy consumption for a three-phase installation compared to the calculation without taking into account power losses. For a single-phase installation, the increase in energy consumption is 7.38%. The application of

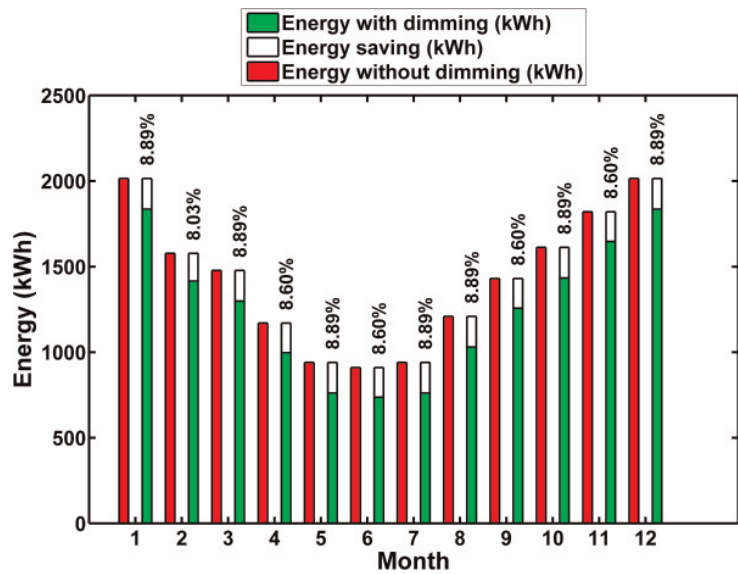


Figure 3.
The volume of electricity consumed in the analysed variants on a monthly scale without energy losses.

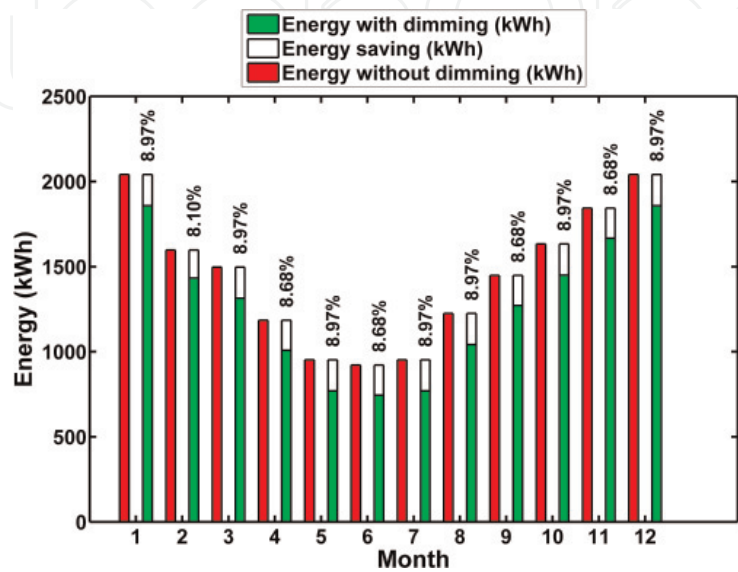


Figure 4.
The volume of electricity consumed in the analysed variants on a monthly scale with three-phase energy losses.

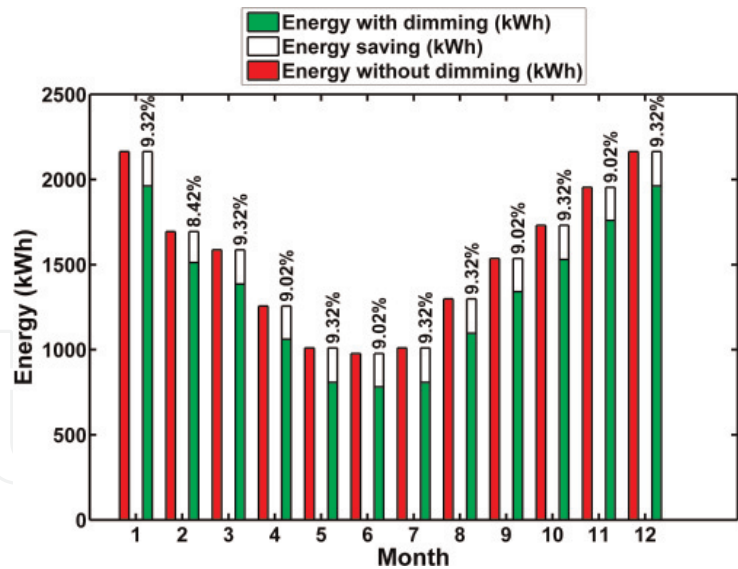


Figure 5.
The volume of electricity consumed in the analysed variants on a monthly scale with single-phase energy losses.

the control luminous flux results in reduced energy consumption. For the three-phase system, the energy consumption increased by 1.16% compared to the calculations without taking losses into account. The increase in energy consumption is 6.66% for a single-phase installation.

Analysing the monthly consumption of active energy, the smallest values occur in the spring and summer months (May, June, July), which is closely related to the working time. Also, in those months, there were the smallest active energy losses. For installations with luminaires operating at a constant power, they are

Month	LED with dimming				
	E_T	E^{3P}_T	E^{1P}_T	$E^{3P}_{\Delta P}$	$E^{1P}_{\Delta P}$
	(kWh)	(kWh)	(kWh)	(kWh)	(kWh)
January	1836	1858	1962	22	126
February	1416	1433	1512	17	96
March	1299	1314	1385	15	87
April	997	1008	1061	11	65
May	761	770	808	8	47
June	737	745	782	8	45
July	761	770	808	8	47
August	1030	1042	1097	12	67
September	1257	1272	1341	15	84
October	1433	1450	1530	17	96
November	1647	1667	1760	20	113
December	1836	1858	1962	22	126
Annual	15,010	15,184	16,009	174	999

Table 8.
Summary of the calculated values of energy consumption by lighting installation without and including losses with dimming.

26 kWh, and for installations working according to the schedule, they are equal to 22 kWh—for three-phase. Energy losses through the use of dimming have been reduced about 15% in three-phase installation. For a single-phase installation, the

Month	LED without dimming				
	C_T	C^{3P}_T	C^{1P}_T	$C^{3P}_{\Delta P}$	$C^{1P}_{\Delta P}$
	(EUR)	(EUR)	(EUR)	(EUR)	(EUR)
January	231.56	234.54	248.66	2.98	17.10
February	181.27	183.60	194.65	2.33	13.38
March	169.81	172.00	182.35	2.18	12.54
April	134.46	136.19	144.38	1.73	9.93
May	108.06	109.45	116.04	1.39	7.98
June	104.58	105.92	112.30	1.35	7.72
July	108.06	109.45	116.04	1.39	7.98
August	138.94	140.73	149.20	1.79	10.26
September	164.34	166.45	176.47	2.11	12.13
October	185.25	187.63	198.93	2.38	13.68
November	209.15	211.85	224.60	2.69	15.44
December	231.56	234.54	248.66	2.98	17.10
Annual	1967.05	1992.36	2112.30	25.31	145.24

Table 9.
Summary of the calculated energy cost caused by lighting installation without and including losses without dimming.

Month	LED with dimming				
	C_T	C^{3P}_T	C^{1P}_T	$C^{3P}_{\Delta P}$	$C^{1P}_{\Delta P}$
	(EUR)	(EUR)	(EUR)	(EUR)	(EUR)
January	210.98	213.51	225.49	2.53	14.51
February	162.67	164.60	173.72	1.93	11.04
March	149.23	150.96	159.18	1.74	9.95
April	114.53	115.83	121.96	1.30	7.42
May	87.48	88.42	92.87	0.94	5.39
June	84.66	85.57	89.87	0.91	5.21
July	87.48	88.42	92.87	0.94	5.39
August	118.35	119.69	126.02	1.34	7.67
September	144.41	146.10	154.04	1.68	9.63
October	164.67	166.60	175.75	1.94	11.09
November	189.23	191.49	202.17	2.26	12.94
December	210.98	213.51	225.49	2.53	14.51
Annual	1724.67	1744.70	1839.40	20.04	114.73

Table 10.
Summary of the calculated energy cost caused by lighting installation without and including losses with dimming.

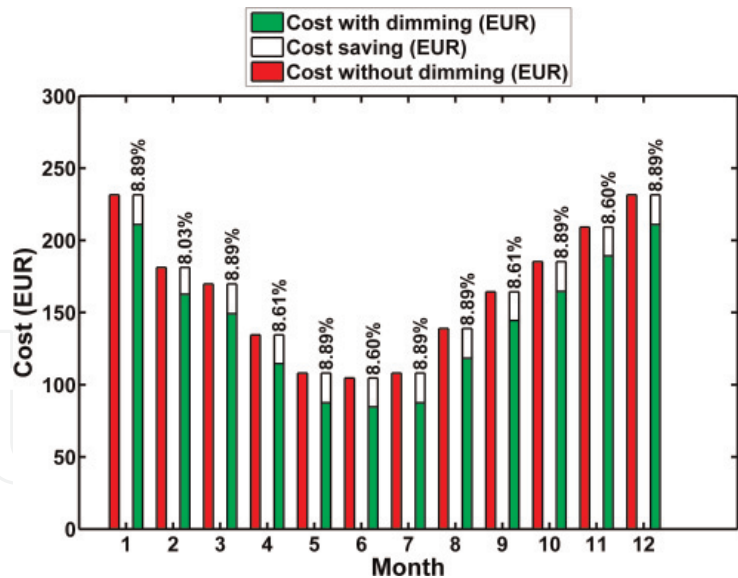


Figure 6. Cost of electricity consumed in the analysed variants on a monthly basis without energy losses.

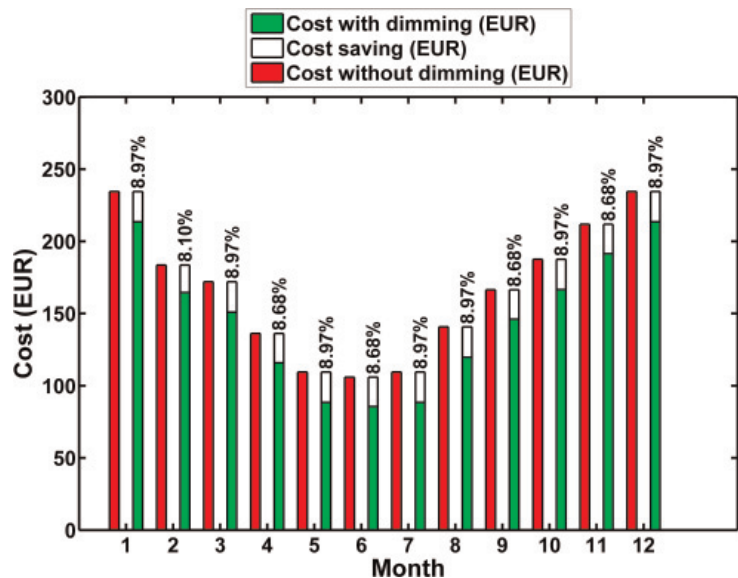


Figure 7. Cost of electricity consumed in the analysed variants on a monthly basis with three-phase energy losses.

losses are several times greater. The use of dimming caused a reduction of energy losses equal to 18.25%.

In the next part of the analysis, the estimated costs of electricity consumption of the analysed lighting installation were calculated. Similarly as before, electricity costs were calculated taking into account the losses of active power in the single- and three-phase network. The active energy price of 0.1194 € for 1 kWh was adopted for the calculation. This is the average price for customers non-habitable in the EU based on [35]. The calculation results are summarised in **Table 8** for installation without dimming and in **Table 9** for installation with dimming. **Figures 6–8** and **Table 10** show the calculated electricity cost of analysed lighting installation variants on a month-per-month scale.

The use of dimming resulted in savings of 8% per month compared to installations without dimming. The annual cost of active energy losses for three-phase installation without dimming is 25.31 €. For the same installation, the costs of the active energy losses with dimming are 20.04 €. For a single-phase installation, these costs are 145.24 € (with dimming) and 114.73 € (without dimming), respectively.

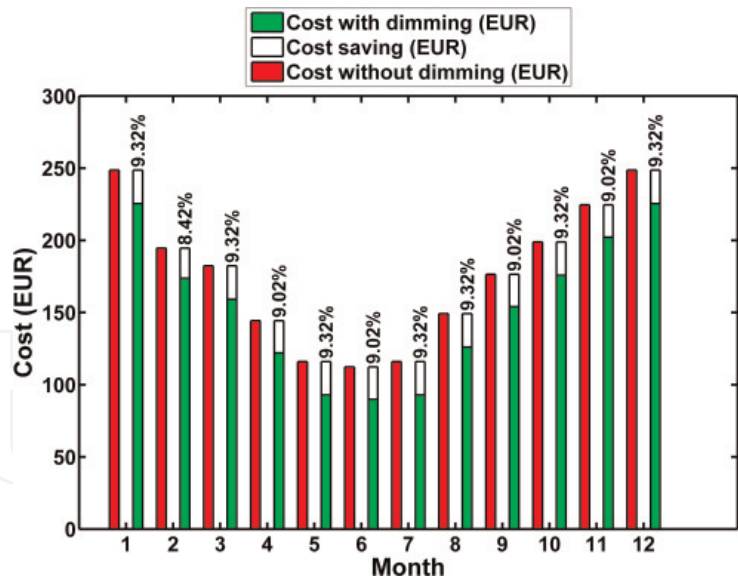


Figure 8.
Cost of electricity consumed in the analysed variants on a monthly basis with single-phase energy losses.

The costs of energy losses in a single-phase installation are more than four times higher than in a three-phase installation. The conclusion is that single-phase installations should be avoided as far as possible. If this is not possible, the energy efficiency calculations, energy balance and operating cost analysis should take into account the losses of power (energy). The financial savings achieved through dimming are proportional to the energy savings. On an annual perspective, dimming allowed to achieve financial savings:

- For the installation without taking into account active power losses is 242.38 €
- For the installation taking into account the active power losses for a three-phase installation is 247.66 €
- For the installation taking into account the active power losses for a single-phase installation is 272.90 €

The use of dimming has brought the greatest savings for a single-phase installation. This is due to the reduction of power losses in the lighting installation as a result of dimming.

6. Conclusions

The chapter presents a method of estimating electricity consumption and operating costs of road lighting installations. This method allows for the taking into account of active power losses in the calculations. These are analytical dependencies that can be used at the design stage. An analytical dependence allowing to calculate the power of auxiliary devices has been proposed. In addition, dependencies allowed for the calculation of energy consumption and electricity costs were presented. The usefulness of the proposed method is illustrated by a calculation example.

The calculation was performed for an example lighting installation consisting of 30 road luminaires. The impact of active power losses on the energy performance indicator, energy consumption and electricity costs was estimated.

On the basis of the made analysis, the following conclusions may be concluded:

- In order to use dimming, it is necessary to calculate the lighting parameters on the road first.
- On the basis of calculations of lighting parameters on the road, it is possible to determine dimming for the assumed lighting class of the road.
- The omission of active power losses for a three-phase installation does not significantly affect the accuracy of calculations.
- For a single-phase installation, the active power losses should not be omitted because the calculation can then be made with an error of more than 5%.

The energy performance indicators PDI and AECI may be used to estimate the energy efficiency of a road lighting installation. Road lighting design is typically developed as a multivariant design. The designer decides which of them should be selected for further analysis on the basis of the values of these indicators. In summary, when making a decision, the designer must give priority to the following considerations when making a decision for road safety. Electricity savings must not be given higher priority than road safety.

Conflict of interest

The authors declare no conflict of interest.

Nomenclature

D_P	the power density indicator ($\text{W lx}^{-1} \text{ m}^{-2}$)
D_P^{1P}	the power density indicator with single-phase losses ($\text{W lx}^{-1} \text{ m}^{-2}$)
D_P^{3P}	the power density indicator with three-phase losses ($\text{W lx}^{-1} \text{ m}^{-2}$)
E_i^{ah}	the maintained average horizontal illuminance of the i -th subarea (lx)
A_i	the size of the subarea “ i ” lit by the lighting installation (m^2)
D_E	the annual energy consumption indicator (Whm^{-2})
D_E^{1P}	the annual energy consumption indicator with single-phase losses (Whm^{-2})
D_E^{3P}	the annual energy consumption indicator with three-phase losses (Whm^{-2})
P	total active power of the lighting circuit (installation) (W)
P_k	active power of the k -th luminous point (light source; lamp device; any other devices such as a spotlight control unit, switch or photocell; and the component associated with the luminous point and necessary for its operation) (W)
P_{ad}	total active power of all devices not included in P_k but necessary to operate a road installation such as a remote switch or photocell, centralised light control or centralised management system, etc. (W)
k_{red}^P	power reduction factor
k_{red}^{AD}	power reduction factor of additional equipment
P_{Lum}	active power of the luminaire (W)
$P_{Lum}^{\%}$	active power of the luminaire (percent of rated power)

Q_{Lum}	reactive power of the luminaire (var)
$Q_{Lum}^{\%}$	reactive power of the luminaire (percent of rated power)
PF_D	displacement power factor
PF_{DD}	distortion power factor
$tg\varphi$	tangent φ
THD_I	total harmonic distortion of the current
Φ_{lum}	luminaire flux (lumen)
$\Phi_{lum}^{\%}$	luminaire flux (percent of rated flux)
L_{avg}	average road surface luminance (cd/m ²)
U_0	total uniformity
U_I	longitudinal uniformity
f_{TI}	threshold increment
P_{inst}	total active power of the luminaire (W)
P_{inst}^{red}	total active power of the luminaire with reduced their power (W)
P^{red}	total active power of the lighting circuit (installation) with reduced luminaire power (W)
n_{lp}	the number of lighting points associated with the lighting installation or the representative section whichever is used in the calculation
ΔP_{Σ}	total active power losses (W)
ΔP_{Σ}^{3p}	total active power losses in three-phase installation (W)
ΔP_{Σ}^{1p}	total active power losses in single-phase installation (W)
ΔP_C^{1p}	active power losses in the power cable in single-phase installation (W)
ΔP_C^{3p}	active power losses in the power cable in three-phase installation (W)
ΔP_N	active power losses in the neutral conductor of the power cable (W)
ΔP_W	active power losses in the pole wire (W)
ΔP_{PPB}	active power losses in the protection in the lighting switchboard (W)
ΔP_{PP}	active power losses in the protection in the pole switchboard (W)
ΔP_R	active power losses in the contactor/relay controlling the lighting installation in the switchboard (W)
n	number of luminaires per phase
l_{01}	distance of the first luminaire from the lighting switchboard (m)
l	distance between the poles (m)
l_{PW}	length of wire in the pole (m)
γ_C	conductivity of the conductor the power cable (m/Ωmm ²)
γ_{PW}	conductivity of the wire the pole (m/Ωmm ²)
S_C	cross-section of the conductor of the power cable (mm ²)
S_{PW}	cross-section of the of the wire the pole (mm ²)
I_{Lum}	luminaire current (A)
I_{hLum}	harmonic currents of the zero sequence for h = 3,9,15 and so on (A)
I_{LI}	lighting installation current (A)
R_{PW}	resistance of the wire connecting the pole switchboard to the luminaire (Ω)
R_{PPB}	resistance of the protection in the lighting panelboard (Ω)
R_{MCB}	resistance of the miniature circuit breaker (Ω)
I_{MCB}	current of the miniature circuit breaker (A)
R_{PFB}	resistance of the fuse carrier (Ω)
R_{PBF}	resistance of the fuse (Ω)
R_{PP}	resistance of the protection in the pole (Ω)
R_R	resistance of the relay (Ω)
E_T	active energy consumed by the lighting installation without losses (kWh)
t_{use}	lighting time (h)
E_{ad}	total active energy of all auxiliary devices not included in P_k (kWh)


w	number of auxiliary devices
n_d	number of working period of auxiliary devices
n_{dim}	number of dimming period of luminaires
t_{use}^{ad}	working time of auxiliary devices (h)
E_{SLI}	total active energy consumed by the lighting installation with losses (kWh)
E_T^{3P}	active energy consumed by the lighting installation with three-phase losses (kWh)
E_T^{1P}	active energy consumed by the lighting installation with single-phase losses (kWh)
$E_{\Delta P}^{3P}$	three-phase active energy losses (kWh)
$E_{\Delta P}^{1P}$	single-phase active energy losses (kWh)
C_T	cost of electricity consumed in the installation without energy losses (EUR)
C_T^{3P}	cost of electricity consumed in the installation with three-phase losses (EUR)
C_T^{1P}	cost of electricity consumed in the installation with single-phase losses (EUR)
$C_{\Delta P}^{3P}$	cost of three-phase losses (EUR)
$C_{\Delta P}^{1P}$	cost of single-phase losses (EUR)

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