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Abstract

Energy efficiency and light pollution are important issues in modern lighting technology. The field of electric lighting is characterized by the potential for large savings to be made and the possibility of the reduction of unwelcome threats. However, the issues of energy efficiency and light pollution have so far not been considered within the context of floodlighting. The main aim of this paper is to present the main considerations in this area. This analysis is based on computer simulations and a proposal for the assessment of these problems is carefully described. Additionally, the connection of visual effect to energy efficiency and light pollution is presented by means of the variant approach.

Keywords: floodlighting, energy efficiency, light pollution

1 Introduction

Energy efficiency and light pollution are the most crucial issues in modern lighting technology. (GALLAWAY, OLSEN, MITCHEL, 2010, , CINZANO, FALCHI, 2014, JOHANSSON, KULLER, PEDERSEN, 2015, GRAYAL, 2017, HANEL, et al. 2018). The main impact of these problems is in relation to environmental protection and the irrational use of electrical energy, which is perceived as an unwelcome phenomenon in many different engineering areas, such as that of lights and lighting. The area of lighting has much to offer the environment, due to the high potential for electrical energy savings to be made (IEA, 2006, website of IEA). Technical reports, requirements, legal regulations and standards for energy-efficient lighting are currently being developed all over the world. However, these are mainly related to indoor lighting and street lighting (CEN, 2010, PRACKI, 2011, CEN, 2015). So far, no document has been created that connects the issue of energy efficiency with architectural lighting (floodlighting). Although the latest technical reports and standards for outdoor lighting have taken into account the phenomena of skyglow, spilt light and obtrusive light (environmental light pollution issues), floodlighting has been totally (or almost totally) omitted (CEN, 2007, CIE, 1993, CIE, 1997, CIE 2017). At first, this seems to be justified, due to the fact that electric installations, such as lighting, are characterized by a fairly low value of installed power (only a few dozen kilowatts or so) (SARAIJI, SAJU OOMMEN, 2012, SŁOMIŃSKI, KRUPIŃSKI, 2018). However, this does not justify the lack of any specific guidance or regulations (SKARŻYŃSKI, 2018). After all, the occurrence of the phenomenon of light pollution is primarily associated with external lighting (including floodlighting), due to its significant effect on skyglow, obtrusive light, and even on the issue of glare (SŁOMIŃSKI, KRUPIŃSKI 2018, MANGKUTO, et al., 2018). It is a well-known fact that the impression of lighting designs is subjective (DUGAR, 2016). Up to now, floodlighting designs have been evaluated solely on the basis of a subjective assessment of the beauty of the visual effect obtained, both at the design stage and just after implementation (ŻAGAN, KRUPIŃSKI, 2016, WACHTA, BARAN, LEŚKO, 2018). Therefore, it seems that there is also a strong need to find a method for the assessment of this type of lighting from the perspective of engineering accuracy (SKARŻYŃSKI, ŻAGAN 2018). The balance between visual effect and engineering correctness in relation to energy efficiency and light pollution in architectural lighting should be described by using a simple, but mandatory evaluation system (SKARŻYŃSKI, 2018). Some elements of such an evaluation system are presented in this paper.

2 Metrics for the assessment of energy efficiency and light pollution in floodlighting

2.1 New metrics available in the literature

Up to now, average luminance has been the only technical (engineering) parameter of floodlighting design which has characterized the result of illuminating a given facade (CIE, 1993). Proposed luminance levels are presented in one of the reports of the International Commission on Illumination – CIE, and they are as follows: 4, 6, 12 cd/m2 (CIE, 1993). The lowest luminance value for floodlighting an object is reserved for areas in which the ambient brightness is relatively low, e.g. rural areas. However, the highest luminance value for floodlighting an object is recommended for areas with high ambient brightness, e.g. city centers. This technical report does not indicate how to calculate the recommended luminance value at the design stage or how to verify it after implementation. (There are no guidelines related to the methodology of measurement, equipment to be used, etc.). This fact, and the strong connection between floodlighting and the issues of energy efficiency and light pollution has triggered the creation of new metrics that may be useful in the field of the assessment of the engineering correctness of a proposed lighting solution. Definitions of new metrics have already been presented several times in other publications (SKARŻYŃSKI, 2018). However, in order to make it easier for the readers of this article to understand the content presented in it, they will also be quoted in this paper, both in descriptive form and with the help of appropriate mathematical formulas.

The Floodlighting Utilisation Factor (FUF) is the ratio between the useful luminous flux that reaches the designated area (the object to be floodlit) and causes a specific visual effect (in the form of luminance), and the total luminous flux coming from all light sources used in a given project (1). The definition of FUF is based on the basic definition of the lighting utilization factor, but in this case the parameter is applicable within a completely new area of lighting.

The Loss of Luminous Flux parameter is basically defined by formula (2). It is the difference between the sum of luminous fluxes from all the luminaires and the useful luminous flux. It describes that part of the luminous flux from all luminaires that is not aimed at the object and is scattered around near the illuminated object. In general, this is a direct cause of the phenomenon of light pollution due to floodlighting.

The Maximum Floodlighting Utilisation Factor defines the maximum theoretical value of FUF for a particular design. It is defined as the ratio (3) of total luminous flux emitted from all luminaires used, and the total luminous flux coming from all light sources used in the lighting solution. Its value is related to the quality of manufacture of the lighting equipment in terms of LOR (Luminaire Output Ratio).

The Coefficient of Floodlighting Utilisation Factor is defined as the proportion between the value of the Floodlighting Utilisation Factor for a particular lighting solution and the maximum value of the Floodlighting Utilisation Factor for this solution (4). It is the simplest way of describing the quality of the lighting equipment used in a particular concept. What is more, it can be very useful in the preliminarily assessment of a design, in relation to energy efficiency and light pollution

The Energy Floodlighting Utilisation Factor is the percentage value of the product of the maximum efficiency of illumination and the illumination efficiency obtained for a given lighting solution (5). This parameter directly refers to the effective use of power installed in a given floodlighting concept. The main purpose of this metric is to emphasize how low electricity conversion is within the area of floodlighting.

$$FUF = \frac{\Phi_u}{\Phi_{t0}} \cdot 100\ [\%] \quad (1)$$

$$FUF_{max} = \frac{\Phi_{tlum}}{\Phi_{t0}} \cdot 100\ [\%] \quad (2)$$

$$CFUF = \frac{FUF}{FUF_{max}} \cdot 100\ [\%] \tag{3}$$

$$FUF_{en} = \frac{FUF \cdot FUF_{max}}{100}\ [\%] \tag{4}$$

$$\Phi_{tlum} = \Phi_u + \Phi_{loss} [lm] \tag{5}$$

where

FUF	is the Floodlighting Utilisation Factor in %
FUF_{max}	is the Maxiumum Floodlighting Utilisation Factor in %
$CFUF$	is the Coefficient of Floodlighting Utilisation Factor in %
FUF_{en}	is the Energy Floodlighting Utilisation Factor in %
Φ_u	is the useful luminous flux in lm
Φ_{loss}	is the loss of luminous flux in lm
Φ_{t0}	is the total luminous flux of light sources in lm
Φ_{tlum}	is the total luminous flux of luminaires in lm

2.2 Oversizing Luminance (OL)

Oversizing luminance is the ratio between the average luminance obtained and the recommended average luminance (6-7). This parameter is very important due to the fact that it is directly connected to the energy efficiency of a given floodlighting solution. By calculating or measuring its value, a lighting designer can precisely determine what level of average luminance characterizes the floodlighting design. This makes it possible to correct the power (luminous flux) of the luminaires used in the design. This can be done by using a suitable control system (e.g. dimming of luminaires) or by replacing the luminaires with ones of a higher or lower power (luminous flux) depending on the oversizing luminance obtained.

$$OL = \frac{L_O}{L_A} [-] \tag{6}$$

$$L_O = \frac{\rho_{avg} \Phi_u}{\pi S} [\frac{cd}{m^2}] \tag{7}$$

where

OL	is the oversizing luminance
L_O	is the obtained average luminance of the floodlighting design
L_A	is the assumed average luminance of the floodlighting design
ρ_{avg}	is the average reflectance factor of the illuminated area
S	is the illuminated area

3 Factors having an impact on visual effect, energy efficiency and light pollution in floodlighting

In the course of this research, some factors were observed that could cause significant changes in both the energy efficiency and light pollution metrics, as well as to the planned visual effect of the floodlighting. These have already been described in the literature (ŻAGAN, KRUPIŃSKI, 2016), and they are as follows:

- the method of floodlighting
- the arrangement and directionality of the lighting equipment
- the photometric solids of the lighting equipment
- the quality of the lighting equipment (light output ratio)
- the spectral power distribution (SPD) of the light source and the spectral distribution

- the reflectance factor of the illuminated material

Each of these factors has a different impact, and it is crucial to analyse all the factors carefully during the process of designing architectural lighting. Research has shown that improving the design in terms of all these factors put together is sometimes not possible. Nevertheless, it is possible to improve the design, and find a balance between the visual effect and those technical metrics that are directly related to energy efficiency and light pollution. In addition, awareness of the specific factors that can significantly affect both the visual effect and the energy efficiency and light-polluting effect of a given floodlighting design, enables a more conscious design of this type of lighting to be made. Of course, such an analysis must be supported by the appropriate simulations and calculations (with appropriate assumptions) (SKARŻYŃSKI, 2018). These metrics make it possible to determine, in an unequivocal manner, whether or not, for example, by changing the directionality of luminaires, the new metrics have improved the visual effect, and whether or not the original lighting concept has been disturbed. An example of such an analysis, with reference to an example of a floodlighting design, is presented in the next two chapters of this paper.

4 Study of the balance between visual effect and engineering correctness in the example of the White Pavilion floodlighting design

It was decided to illustrate the factors for improving energy efficiency and reducing light pollution in relation to floodlighting, discussed in the previous chapter, using computer-simulated examples for a selected object. The White Pavilion, located in the Royal Lazienki Museum in Warsaw, was chosen as suitable for conducting simulations and calculations. In accordance with the guidelines of floodlighting, a sufficiently precise computer model of the object was created, as well as a floodlighting concept, based on the Accent Method. Figures 1 and 2 show the visual effect and luminance distribution of the Accent Method of floodlighting the White Pavilion. The effects obtained are consistent with floodlighting guidelines (ŻAGAN, KRUPIŃSKI, 2016). A basic approach is presented here, which means that the design process was stopped at the moment when it was assumed that the visual effect obtained had met the design expectations (with regard to the method of floodlighting, guidelines of floodlighting, lighting equipment used, etc.). Therefore, figures 1 and 2 show the basic directionality of lighting fixtures, with an axially symmetrical luminous intensity distribution (LID) and a neutral CCT of light sources. In order to adequately visualize the changes (either improvement or deterioration) in the values of the new parameters of energy efficiency assessment and light pollution in this floodlighting design, the following changes were made in relation to the initial concept (visualisation and luminance distribution):

- basic directionality, axially symmetrical LID, warm CCT (fig. 3 and 4)
- altered directionality, axially symmetrical LID, neutral CCT (fig. 5 and 6)
- altered directionality (reduced power), axially symmetrical LID, neutral CCT (fig. 7 and 8)
- basic directionality, asymmetrical LID, neutral CCT (fig. 9 and 10)

Figure 1 – Initial visualisation: basic directionality, axially symmetrical LID, neutral

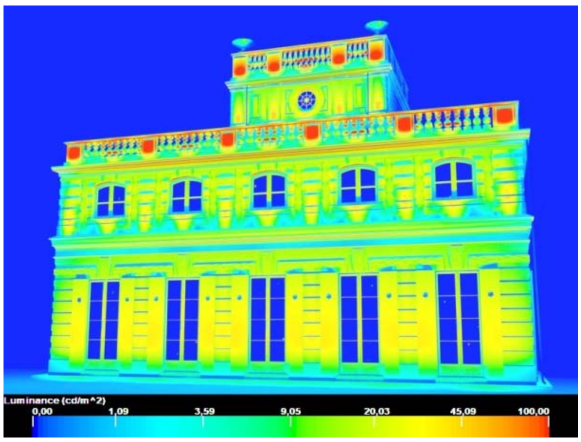

Figure 2 – Initial luminance distribution: basic directionality, axially symmetrical

CCT

LID, neutral CCT

Figure 3 – Amended visualisation: basic directionality, axially symmetrical LID, warm CCT

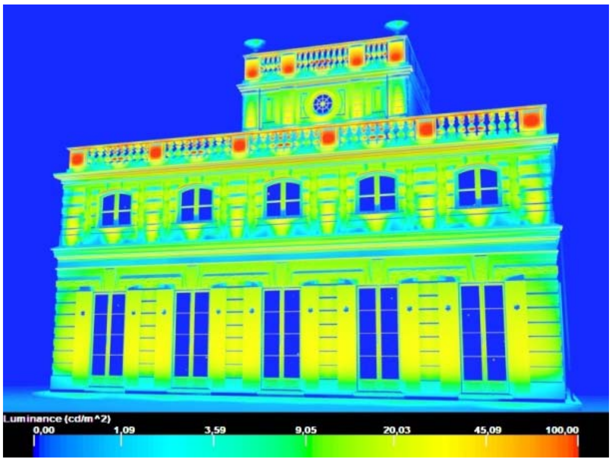

Figure 4 – Amended luminance distribution: basic directionality, axially symmetrical LID, warm CCT

Figure 5 – Amended visualisation: altered directionality, axially symmetrical LID, neutral CCT

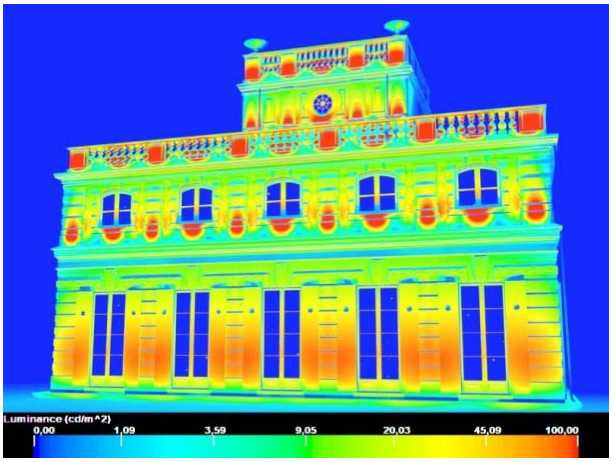

Figure 6 – Amended luminance distribution: altered directionality, axially symmetrical LID, neutral CCT

Figure 7 – Amended visualisation: altered directionality (reduced power), axially symmetrical LID, neutral CCT

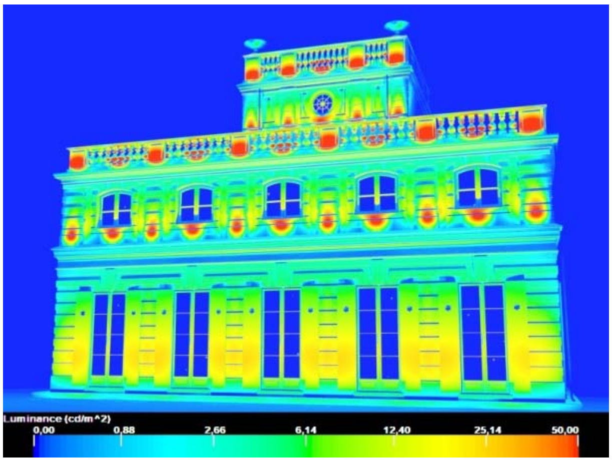

Figure 8 – Amended luminance distribution: altered directionality (reduced power), axially symmetrical LID, neutral CCT

Figure 9 – Amended visualisation: basic directionality, asymmetrical LID, neutral CCT

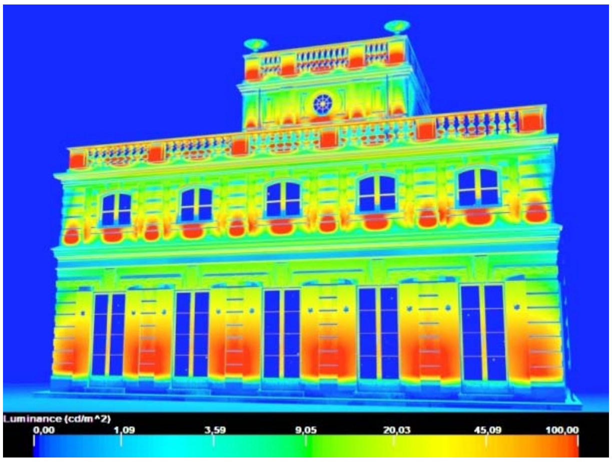

Figure 8 – *Amended luminance distribution:* basic directionality, asymmetrical LID, neutral CCT

5 Results

All calculations were carried out in accordance with the recommendations available in the literature (SKARŻYŃSKI, 2018). It appears that there are some differences in the values obtained for particular metrics of energy efficiency and light pollution assessment, in relation to a specific aesthetic effect (Figure 1-10 and table 1). These cases have been selected in this way so that they can be compared, and the impact of a given factor on a particular metric and the visual effect obtained can be determined.

Table 1 – Summary of useful data and calculation of new metrics for particular variants of the floodlighting of the White Pavilion

Figure	1 & 2	3 & 4	5 & 6	7 & 8	9 & 10
LID	axially-symmetrical	axially-symmetrical	axially-symmetrical	axially-symmetrical (reduced power)	asymmetrical
Aiming	basic	basic	altered	altered	basic
CCT	neutral white	warm white	neutral white	neutral white	neutral white
$P_s\,[W]$	780	780	780	217	780
$\Phi_{t0}[lm]$	55 698	45 446	55 698	15 472	55 698
$\Phi_{top}[lm]$	43 774	35 544	43 774	12 159	43 774
$\Phi_u[lm]$	24 507	19 865	35 090	7660	31377
$\Phi_{nu}[lm]$	19 267	15 679	8684	4499	12 397
$FUF\,[\%]$	44	44	63	63	56
$FUF_{max}[\%]$	79	78	79	79	79
$CFUF\,[\%]$	56	56	80	80	72
$FUF_{en}[\%]$	35	34	49	49	44
$L_o[\frac{cd}{m^2}]$	31	30	44	12	39
$OL[-]$	2,5	2,5	3,6	1,0	3,3

First of all, it should be emphasized that, by introducing appropriate changes in the initial floodlighting concept, a conscious method of influencing both the improvement of energy efficiency and the reduction of light pollution from a given floodlighting design is possible to be achieved. These changes consist of the appropriate aiming of lighting fixtures (thus giving the best impact), the appropriate change in the LIDs of the luminaires used and the change in the spectral power distribution of light sources (by changing their CCT). As a result, the initial design is characterized by the worst effect in terms of the energy efficiency and light pollution values of the new metrics: the useful luminous flux is the smallest, as is the FUF (44%) and the CFUF (56%). In addition, the calculations show that it is very difficult to accurately determine the average luminance of an illumination project only on the basis of the generated luminance distribution. In the case of the initial design, the oversizing of luminance is 2.5. This means that the power (luminous flux) of the luminaires used could be reduced by a factor of 2.5 to obtain the average luminance value recommended for this type of area (12 cd/m2). All parameters are improved when the directionality of luminaires is changed, as well as in the case where the LID is changed from being axially symmetrical to asymmetrical. The useful luminous flux is significantly increased, the FUF reaches over 56% and the CFUF increases to over 72%. However, if the CCT of the light source is changed (from neutral white to warm white), all metrics remain unchanged, apart from the loss of luminous flux, which is definitely lower in this case. From an environmental point of view, this is a greatly improved situation. This is balanced by the fact that the LED lighting most commonly found in architectural lighting and exterior lighting has a negative impact on environmental light pollution (BIERMAN, 2012).

In addition to the quantitative aspects discussed above, the quality of the outcome obtained in terms of the most important aspect, the visual effect, should also be analysed. In the case of a change in the directionality of the luminaires (figures 5 and 6), unsightly areas with high luminance were found that disrupted the original concept of floodlighting and these are not acceptable, despite a significant improvement in all the quantitative metrics. However, after power reduction (in terms of luminous flux) - fig. 7 and 8, these areas were reduced significantly, so that the image obtained is acceptable from the point of view of basic floodlighting guidelines. Therefore, it can be stated that it is possible to achieve designs which are satisfactory in both quantitative and qualitative terms. In the case of changing the LIDs from being axially symmetrical to asymmetrical (figures 9 and 10), areas of high luminance also appear. However, it seems that, in this case, a decrease in power (luminous flux), of about 3 times compared to that of the oversizing luminance parameter, would also give a satisfactory result in terms of visual effect. The matter of changing the CCT of the light from neutral white to warm white is a contentious issue in relation to this object, due to the colour of the façade (a white material with a reflectance factor of above 0.6) - fig. 4. However, by keeping the proportions within the luminance distribution and changing the colour contrast (with more emphasized shading - figures 1 and 3) as compared to the case of floodlighting where neutral white CCT is used, the author believes that the visual effect obtained is the most satisfactory. In addition, in this case there is also a reduction in the light pollution caused by the floodlighting of the White Pavilion, which is undoubtedly very desirable

6 Conclusion

This paper presents a new approach to the assessment of a floodlighting design, which takes into account not only the assessment of the visual effect, but also the issues of energy efficiency and light pollution. This means that the assessment of architectural lighting does not have to be done in a purely subjective way (by analyzing the beauty of the visual effect obtained). There is also the possibility of introducing new and useful metrics related to energy efficiency and light pollution. These metrics allow architectural lighting (floodlighting) to be assessed and controlled in a more objective manner, while taking into account the beauty of a given visual effect. Choosing the most appropriate lighting solution is the responsibility of the lighting designer. Using the new metrics of this assessment, he/she is able to complete a floodlighting design in a more conscious manner. A design made with the inclusion of these new metrics can determine not only the beauty of the night time look of an architectural object, but also the engineering correctness of a lighting solution. Therefore, the implementation of a floodlighting design, in both a beautiful and aesthetically-pleasing way, whilst simultaneously ensuring high energy efficiency levels and low levels of light pollution, becomes perfectly possible.

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