energies

MDPI

Article

Assessment of Colorimetric Parameters for HPS Lamp with Electromagnetic Control Gear and Electronic Ballast

Roman Sikora * and Przemysław Markiewicz

Institute of Electrical Power Engineering, Lodz University of Technology, 90-924 Lodz, Poland; przemyslaw.markiewicz@p.lodz.pl

* Correspondence: roman.sikora@p.lodz.pl; Tel.: +48-42-631-25-95

Received: 22 April 2020; Accepted: 2 June 2020; Published: 5 June 2020

Abstract: Road lighting is an important element of road infrastructure influencing on the road safety. It helps road users to identify potential hazards on the road and reduces the risk of a road accident. Improving the energy efficacy of road lighting installations requires using new technologies. Currently, high-pressure sodium (HPS) lamps are still most commonly used in road lighting. Many of the luminaires with HPS lamps are still in good technical condition and there is no economic justification for replacing them (except improving energy efficacy). One of the methods of improving their energy efficacy is to replace the electromagnetic control gear (ECG) with an electronic ballast (EB). This replacement may affect the colorimetric parameters of the HPS lamps. Two methods to the estimation change of colorimetric parameters after the replacement of ECG to EB were used. The first is CIE TN 001:2014 and the second is ANSI/IES TM-30-15. The article also presents the advantages and disadvantages of these methods in relation to the evaluation of changes in colorimetric parameters of HPS lamps after the replacement of the ECG with an EB. After the replacement of ECG to EB, the smallest reduction of R_a (colour rendering index) occurred for the 150 W lamp by 31.30% and the highest reduction for the 70 W lamp by 65.52%. Considering the changes of the fidelity indicator R_f and gamut indicator R_g, their changes are significantly smaller than for R_a. The smallest change of R_f value was observed for a 150 W lamp (6.00%) and the largest for a 70 W lamp by 25.00%. In case of R_g, similar changes were observed—for 150 W lamp by 9.26% and for 70 W lamp by 21.88%. The ANSI/IES TM-30-15 method is more suitable for evaluating colorimetric parameters after replacing ECG with EB. Using only R_a to evaluate changes of HPS lamps colorimetric parameters after replacing the ballast type can lead to incorrect conclusions concerning changes of colorimetric parameters. Based on the ANSI/IES TM-30-15 method, it has been proposed to introduce the $\Delta_{f,g}$ indicator which determines the change of colorimetric parameters based on fidelity and gamut colour indicator.

Keywords: HPS lamp; electromagnetic control gear; electronic ballast; colorimetric parameters; luminous efficacy

1. Introduction

One of the most important objectives of the European Union's energy policy is to reduce electricity consumption. Activities aimed at achieving this goal are also carried out in the area of road lighting, which is widely described in the literature [1–10] and reflected in the standards and legal acts of the European Union [11–17]. The European Commission recommends designing light sources in accordance with eco-design requirements according to the regulations [16]. The EN 13201-5 [18] standard contains recommendations concerning the principles of designing road lighting with minimum energy consumption. Of course, the simplest method to reduce electricity consumption by road lighting installations is to replace light sources or luminaires with modern and energy-saving solutions [19]. At present, such a solution is the luminaires made with LED technology. However, still the largest number of road lighting luminaires for high-pressure sodium (HPS) lamps are used in outdoor lighting since the 60's of the XX century [20–26]. The most important advantages of these lamps include high durability, luminous efficacy and relatively low investment and operating costs. Luminous efficacy of HPS lamps is in the range of 68–150 lm/W [21]. The disadvantages are the relatively high power of these luminaires and low colour rendering index R_a (CRI).

The main purpose of road lighting is to provide appropriate lighting conditions on the road in accordance with legal requirements and standards. The driver's visual system provides about 90% of information necessary for safe driving [20]. The driver uses the visual organ to observe the traffic on the road and in its surroundings, e.g., to observe waiting areas within pedestrian crossings. While driving, the driver must control the indications of the devices on the dashboard, look into the side and rear-view mirrors as well as follow the vertical and horizontal road signs and traffic lights. All these activities are carried out while driving in different road and weather conditions and unfortunately with changing traffic lights [21]. Apart from ensuring proper road lighting conditions, it also affects the evening and night image of urban spaces. It ensures not only road traffic safety but also the generally understood safety and comfort of urban space use [22].

Photometric and colorimetric parameters of light sources (luminaires) have an impact on safety of road traffic. The most important parameters include spectral power distribution (SPD) of emitted radiation, luminous flux, colour tristimulus values, colour temperature, illuminance and colour rendering index (CRI). Ensuring proper colour rendering of perceived objects by light sources is one of their most important properties. Changing the illuminated object colour by the light source can cause many unwanted incidents and phenomena. Information about the methods of colour rendering when illuminating an object is included in the spectral power distribution. A noticeable lack of a given wavelength may cause the observer to perceive it incorrectly. Road lighting helps road users to recognise potential hazards on the road in the form of, for example, an object that suddenly appears on the road and must be recognised quickly and correctly by drivers. There are traffic signs in the vicinity of the road which are made according to the applicable regulations and have characteristic colours. Poor recognition of the colour of the sign may adversely affect road safety. In the event of an traffic accident, the road lighting with a low colour rendering index may cause incorrect description of persons and objects involved, e.g., incorrect description of clothes colours or vehicle body colour. In case of an injury, it is important for the paramedic to know the colour of blood. The bright colour of blood may indicate damage to arterial vessels equivalent to life-threatening injuries [24].

According to the normative requirements, road lighting provides luminance in the range of approx. 0.1 cd/m^2 to 3 cd/m^2. Such a range of luminance corresponds to the conditions of mesopic-twilight vision. During mesopic vision, light is processed in the eye by stamens and posts. In mesopic vision, colour and black-and-white vision combine [27]. In poor lighting conditions, under mesopic vision conditions, the perception of colours, e.g., the Purkini effect, is disturbed. The Purkini effect describes the phenomenon associated with higher visibility of blue colours compared to red. Considering the properties of mesopic vision, it can be concluded that road lighting should ensure high colour fidelity, which will additionally support the vision process [27]. HPS lamps commonly used in road lighting are characterized by a low colour rendering index R_a not exceeding 30 [27]. In the case of LED luminaires or when replacements for high pressure lamps are used, the value of this indicator is significantly higher [28,29]. At present, such a solution is the luminaires made in LED technology [30–32]. Another important issue is to reduce light pollution by road lighting [33].

CRI is a measure of colour rendering developed by CIE [34–36]. The maximum value of this coefficient is 100. Under such illumination, the observer does not distinguish the colour of the illuminated object with the tested and reference light [34–36]. The large number of luminaires for high-pressure sodium lamps in operation is still in good condition for further operation. There would be no economic justification for replacing them. Therefore, these installations are modernized by replacing the electromagnetic control gear (ECG) with an electronic ballast (EB) [37–41]. Electromagnetic control gear is composed of an igniter, a magnetic ballast and a capacitor for compensating the inductive reactive power. Another method of increasing the energy efficiency of a road lighting installation is the use of a central controller supplying the entire lighting installation consisting of luminaires for high-pressure sodium (HPS) lamps with voltages of adjustable parameters [37–41]. However, the most common method is to replace ECG with a properly designed and selected electronic ballast. The literature describes various design solutions of electronic ballasts [41–45]. The use of electronic ballasts also allows to regulate the power (luminous flux) of these lamps. If the electronic ballasts are additionally equipped with communication modules, they can become a part of Smart City system [46]. Depending on the design and operation algorithm of the ballast, it makes changes to the operation point of the HPS lamps. Usually, by replacing the ECG with an EB, the active power of the ballast-lamp system is reduced. In this way, the electricity consumption of the lighting system is obviously reduced. It can therefore be expected that the lamp's radiant power will also be reduced and that the SPD shape may change. A change of the SPD may in turn cause a change in the lamp's colorimetric parameters. The literature has not found any description of the influence of the conversion of ECG by EBs on colorimetric parameters. Therefore, the analysis was made on the basis of measurements made for four high-pressure sodium lamps of rated power 70, 100, 150 and 250 W. The measurements were made for lamps powered by ECG, which were then replaced by EBs dedicated for these lamps.

The paper compares two methods of evaluating colorimetric parameters. These are CIE TN 001:2014 [46] and ANSI/IES TM-30-15 [47]. The paper presents the advantages and disadvantages of these methods in relation to the evaluation of changes in colorimetric parameters of HPS lamps after the replacing of ECG to EBs.

2. Materials and Methods

2.1. CIE Colorimetric Analysis Method

The assessment of colour rendering quality of a light source is measured by the colour rendering index R_a (CRI) defined in CIE 13.3-1995 [34]. This method is currently widely recognized and used in Europe. It consists in comparing the appearance of 14 test colour samples (TCS) with the tested light of a given spectrum and the reference light. Blackbody radiators is used as a reference source. It is used for test sources with colour temperature T_b not exceeding 5000 K. If the corelated colour temperature (CCT) exceeds 5000 K, a mathematical model of the SPD of daylight is used. In order to obtain the appropriate accuracy, the chromaticity of the test and reference source during measurements shall be similar. The difference between the colour of the analysed sample illuminated with the test light and that of the reference light allows the calculation of the partial colour rendering index R_i. The total colour rendering index R_a is calculated as the arithmetic mean of the first eight analysed samples from Equation (1). The maximum value of CRI is 100, which corresponds to the situation when the observer does not distinguish between the colour of the illuminated object with the test and reference light.

$$R_a = \frac{1}{8}\sum_{i=1}^{8} R_i \tag{1}$$

Due to the fact that the value of R_a is calculated from the first eight R_i partial indicator without taking into account the changes for the other test colour samples (TCS), this may cause large discrepancies with relatively small changes in colour temperatures and chromatic coordinates. Chromaticity is one of the most important parameters characterizing light sources. Chromaticity changes or differences in chromaticity are determined in the analysis of many issues, e.g., when determining the chromaticity change with an increase in maintenance life. The difference in chromaticity should also be estimated in case of a change in power supply conditions of a light source. This situation occurs when the ECG to EB is replaced in the luminaire.

One of the methods of determining differences of a light source's chromaticity is the use of Macadam's ellipses. The ellipses determine changes in the chromaticity of light sources which the human eye is unable to distinguish. Macadam's ellipses can be presented both in a CIE 1931 (x, y) and a CIE 1976 (u',v') diagram. For the evaluation of chromaticity changes, n-step ellipses (or n-SDCM—Standard Deviation of Colour Matching) are used. The most common are 3-SDCM and 5-SDCM ellipses. The Macadam's ellipses shown in the CIE 1976 diagram (u',v') and lying near the Planckian locus are similar to a circle. Therefore, CIE TN 001:2014 [46] recommends using u'_c and v'_c centre circles instead of Macadam's ellipses to assess chromaticity changes. This makes the analysis much easier as interpolation of an ellipse of a given size and for a given CCT colour temperature is a complicated and numerically difficult issue. Interpolating these ellipses with a circle with a radius of r does not cause errors with unacceptable values. Similarly, as in the case of the Macadam's ellipse, an n-step circle can be crossed out using the relationship below.

$$(u' - u'_c)^2 + (v' - v'_c)^2 = (0.0011 \cdot n)^2 \quad (2)$$

Also, in this case, 3- and 5-degree circles are used for assessment. The use of circles is recommended only for light sources with a similar chromaticity to Planckian locus [43]. Another indicator described in the CIE that can be used to determine the chromaticity difference is the chromaticity difference $\Delta_{u',v'}$. It is calculated from Formula (3) [48].

$$\Delta_{u',v'} = \sqrt{\left(u'_2 - u'_1\right)^2 + \left(v'_2 - v'_1\right)^2} \quad (3)$$

Chromaticity difference $\Delta_{u',v'}$ is the distance between two points (u'_2,v'_2) and (u'_1,v'_1) in the 1976 CIE diagram (u',v'). This indicator may be used to analyse the chromaticity variations of light sources of any chromaticity.

2.2. IES TM-30-15 Colorimetric Analysis Method

The method of estimating the quality of colour rendering described in IES TM-30-2015 [28] introduces instead of the colour rendering index CRI such quantities as R_f (colour fidelity) and R_f (colour gamut). Similarly, as in the CIE-based method, the tested surface is illuminated with the test and reference light. Blackbody radiators (for colour temperature below 4500 K) or illuminant D56 (for colour temperature above 5500 K) are used as reference sources. According to the guidelines for colour temperature in the range from 4500 to 5500 K, a combination of Planck's blackbody radiators and daylight (mathematical model) is used. This method is described in detail in [47–50]. For the defined 99 samples the differences in colour perception at their illumination are determined by the test and reference source and calculated by their arithmetic mean. The same light sources are used to determine the index of changes in colour saturation. The analysed samples are grouped into 16 colour cells of constant width. The affiliation of a given sample to one of the colour cells is realized on the basis of their similar chromaticity and light exposure. In the next stage, the chromatic coordinates of the sample illuminated by the test and reference light source are calculated. The mean value is determined for each cell in both cases. These 16 points on the colour plane for the test and test light create, after their combination, the test source A_{test} area and A_{ref} area for the reference source. The value of the colour gamut index R_g is calculated from the following Relationship (4).

$$R_g = 100 \cdot \frac{A_{test}}{A_{ref}} \quad (4)$$

In this way, the colour vector graphic (CVG) is created. It can be used to determine changes in colour fidelity and saturation. In the case of a vector whose beginning is at a point for the mean value when illuminating the sample with the test light and the end at the same point for the test light and is directed towards the centre of the graph, there is a decrease of colour saturation within the same cell (colour shades). If the vector is directed opposite, there is an increase of colour saturation in a given cell. In this way, the entire graph for each of the 16 cells can be analysed. However, the CVG interpretation does not give an unambiguous numerical value of the change in hue rendering. In order to compare graphs for two light sources, or the same light source but working at a different point of work, these graphs should be compared.

To assess the chromaticity changes, a graph of the relationship between colour fidelity R_f and colour gamut R_g indicators can be use. These indicators form a complementary system of two measures, which is used to visually illustrate the compromise between fidelity and saturation. Visual comparison of the two points in the R_f vs. R_g graph does not give an unambiguous value for the evaluation of the change in colour rendering. By comparing the colour rendering of two different light sources or the same light source but working under different conditions, a measure of change in saturation and colour fidelity can be made using the R_f vs. R_g chart. Assuming that this measure is the distance between two points ($R_\mathrm{f,2}$,$R_\mathrm{g,2}$) and ($R_\mathrm{f,1}$,$R_\mathrm{g,1}$) this indicator can be described as:

$$\Delta_{f,g} = \sqrt{\left(R_{f,2} - R_{f,1}\right)^2 + \left(R_{g,2} - R_{g,1}\right)^2} \tag{5}$$

The use of this indicator allows the numerical determination of the change in saturation and fidelity of colour rendering.

2.3. Description of Test Objects

Four HPS lamps with rated power of 70, 100, 150 and 250 W were selected for analysis. In the first stage of testing, the lamps are supplying by traditional electromagnetic control gear. It consists of a magnetic ballast and an ignition system. Then, the ECG was replaced by an electronic ballast (EB) made by a reputable manufacturer. The electronic ballast functioned according to the data provided by the manufacturer in the data sheet, the rated power of the lamp system–ballast in normal operation cycle is equal or lower than the nominal power of the lamp. In case of the 70 W lamp, the power of this system is 70 W. For a 100 W, lamp this is 95 W. The power of the ballast–lamp system for 150 W lamp is 140 W. In case of 250 W lamp it is 225 W. The reduced power should be within ±5% of the power specified in the ballast data sheet. The tested electronic ballast has a PFC (power factor correction) and a soft start system. The purpose of the PFC system is to reduce the negative impact of the ballast on the power supply network. Among other things, it reduces the higher harmonics generated to the supply. The soft-start system reduces the inrush current, thus reducing the risk of unnecessary triggering of overcurrent protection, e.g., when installed in a pole switchgear. The manufacturer does not provide information on the lumen reduction value after changing ECG to EB. The catalogue data also does not include information on the change of colorimetric parameters. Estimation of these changes (colorimetric parameters, luminous flux and luminous efficacy) is the subject of this paper.

2.4. Experimental Setup

The scope of analysis includes measurements of colorimetric, photometric and electrical parameters of tested HPS lamps with ECG and EB. The colorimetric measurements are performed using the experimental setup shown in Figure 1a. This experimental setup consists of the AGILENT 6834B programmable power supply, the GLOptic Spectis 5.0 Touch spectrometer and integrating sphere. The AGILENT 6834B power supply is used to always have the same supply voltage of 230 V. Application of the power supply also allowed to supply the tested systems with sinusoidal (non-deformed) voltage. The used spectrometer for measurements allows for the SPD analysis in the range from 200 to 850 nm. Measurements of the electrical parameters and the luminous flux make using the experimental setup shown in Figure 1b. Furthermore, in this case, the AGILENT 6834B programmable power supply is used to supply the tested objects. Luminous flux measurements make with the use of a luxmeter L-100. For the measurements of electrical parameters, a FLUKE 1760 power quality analyser is using.

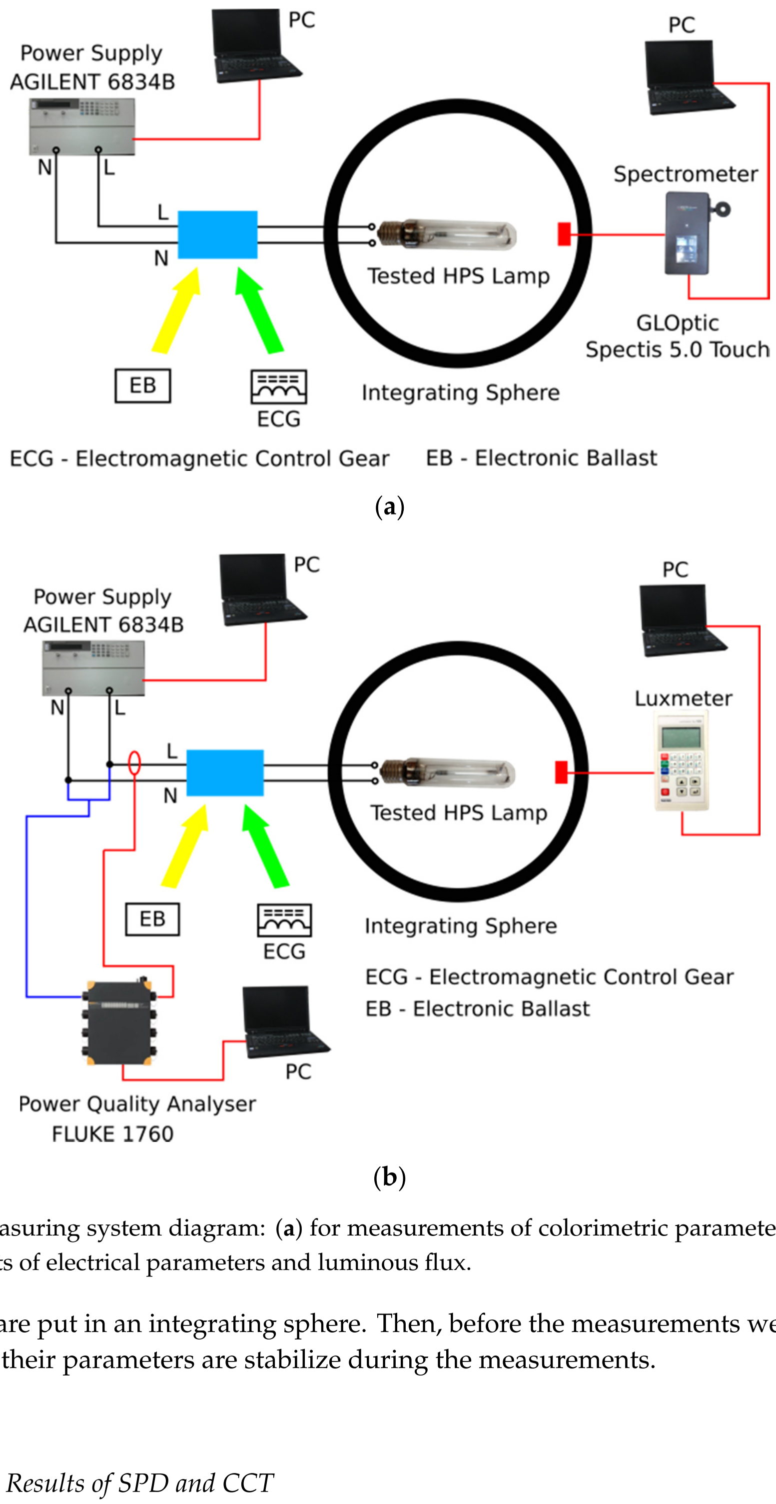


Figure 1. Measuring system diagram: (**a**) for measurements of colorimetric parameters, and (**b**) for measurements of electrical parameters and luminous flux.

HPS lamps are put in an integrating sphere. Then, before the measurements were taken, they are lit for 1 h so that their parameters are stabilize during the measurements.

3. Results

3.1. Measurement Results of SPD and CCT

The aim of the study was to assess the influence of the replacement ECG with an electronic ballast (EB) supplying HPS lamp on its colorimetric parameters. Using GLOptic Spectis 5.0 Touch spectrometer, colorimetric parameters of HPS lamps with ECG and EB are measured. Figure 2a–d shows the SPD of HPS of lamps in the range 380–850 nm. For comparison of the obtained results, the SPD for a HPS lamp of the same power and different types of ballasts are presented in a common graph. The method of operation of the electronic ballast is such, that it reduces the luminous flux in relation to the HPS of lamps with ECG. This phenomenon occurs for all tested lamps. On the basis of the comparison of SPD presented in Figure 2a–d, it is not clear for which wavelengths the biggest differences occurred. Therefore, the percentage difference between the energy for a given wavelength for HPS lamps with ECG and EB is calculated using the Relationship (6). The results of the calculation are shown in Figure 3.

$$\Delta E_I(\lambda) = \frac{E_I^{\mathrm{ECG}}(\lambda) - E_I^{\mathrm{EB}}(\lambda)}{E_I^{\mathrm{ECG}}(\lambda)} \cdot 100\% \tag{6}$$

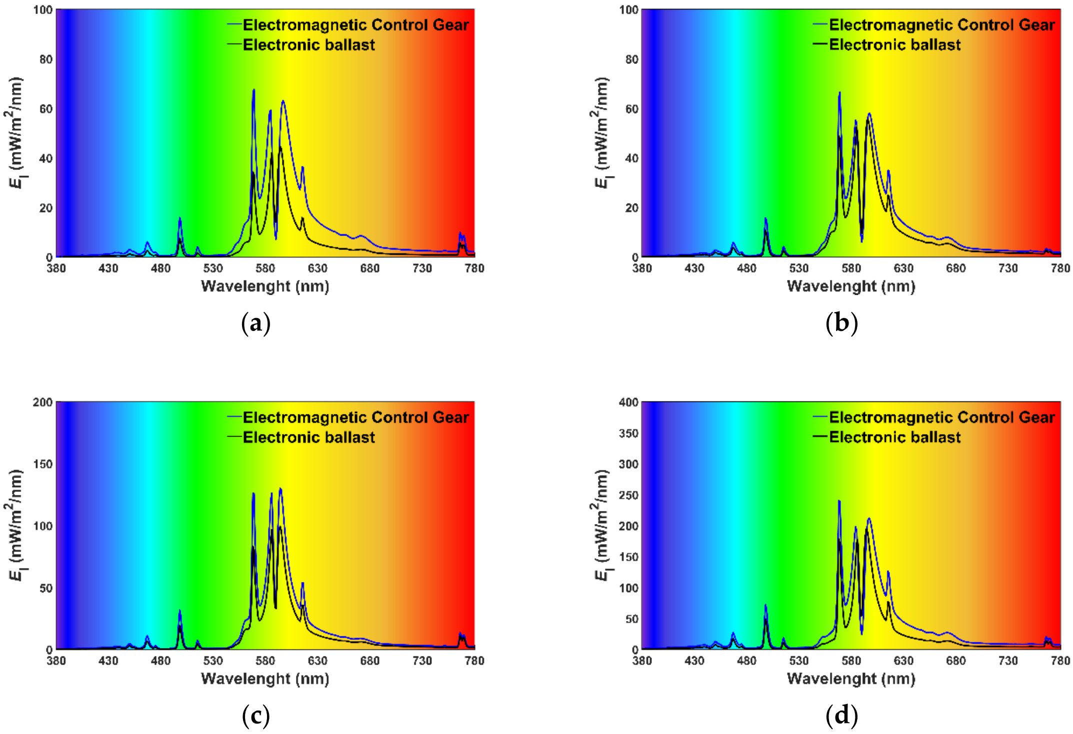


Figure 2. Comparison of spectral power distribution (SPD) for: (**a**) the 70 W high-pressure sodium (HPS) lamp with electromagnetic control gear (ECG) and an electronic ballast (EB), (**b**) the 100 W HPS lamp with ECG and an EB, (**c**) the 150 W HPS lamp with ECG and an EB, (**d**) and the 250 W HPS lamp with ECG and an EB.

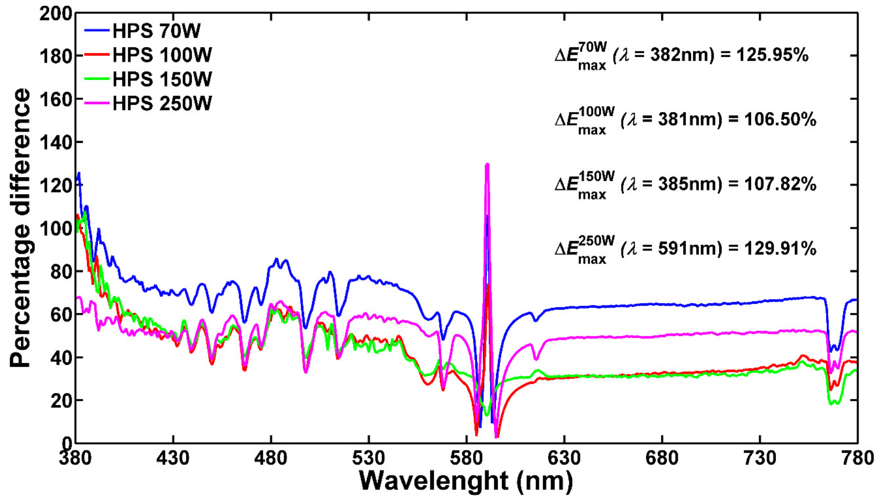


Figure 3. Calculated wavelength differences between SPD for lamps with ECG and EB.

For HPS lamps with a rated power of 70 W, 100 W and 150 W, the greatest differences of radiated energy values occurred in the blue light range. For 70 W HPS lamps, the biggest difference was for the wavelength λ = 382 nm and it is 125.95%. For 100 W and 150 W HPS lamps, the biggest differences are observed for 381 nm and 385 nm wavelengths. The percentage energy difference is 106.50% and 107.82% respectively. For 250 W lamps only, the maximum difference in radiation energy is found at λ = 591 nm and it is 129.91%.

The reduction of radiation energy is cause by two factors. The first is, as mentioned earlier, the reduction of the active power of the lamp-ballast system. The aim of this operation is to improve the energy efficacy of the lighting system. This function is performed by an appropriate control algorithm implemented in the electronic ballast. Using the experimental setup show in Figure 1b, the luminous flux values of the tested HPS lamps from ECG and EB were measured. The results of the measurements are show in Figure 4. For the tested lamps, the percentage value of luminous flux reduction was calculated. This is also illustrated in Figure 4. The highest luminous flux reduction occurs for 100 W HPS lamps and is 34.67%. For 250 W HPS lamps, this reduction is 20.00% and is the lowest achieved value. When analysing the percentage differences of SPD for both cases, it was found that they are greater than the reduction of luminous flux. These differences are greater for all tested lamps. Therefore, the second reason for the reduction of spectral power density is the change of lamp operating point. This is caused by a change of the lamp supplying voltage e.g., the rms value of its frequency and curve shape. A change of the operating point affects the shape of the SPD.

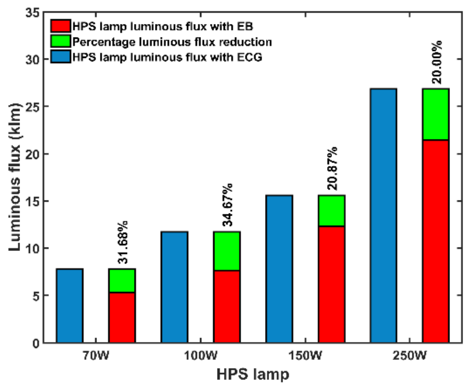


Figure 4. Comparison of the luminous flux values with his percentage reduction.

Analysis of the SPD does not give a clear answer to the question how the replacement of the ballast affects the change of colorimetric parameters. Another parameter that can be used for analysis is colour correlated temperature (CCT). On the basis of the measured CCT values for the tested HPS lamp, it can be concluded that for each of the lamps the replacement of ECG with EB causes a decrease of the colour temperature value. The smallest reduction of colour temperature by 48 K occurs for 250 W lamp (Figure 5). The reduction of CCT is greatest for 100 W lamp and is 77 K. In both analysed cases, the reduction is below 100 K, taken across a border that the human eye can distinguish. It can be assumed quite strictly that the acceptable change of CCT does not exceed 5%. For all tested lamps the CCT value after changing the ballast is within the assumed range. This is illustrated by the acceptable CCT changes (marked as error bar) show in Figure 5.

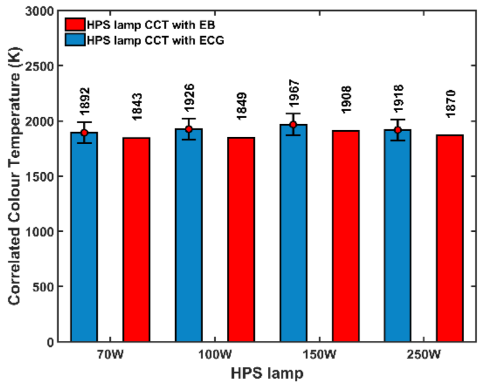


Figure 5. Comparison of the CCT values.

3.2. Chromaticity Difference Analysis

Figure 6 shows the measured chromatic coordinates for HPS lamps with ECG and EB. The replacement of the magnetic ballast with an electronic one causes the chromaticity point to move significantly further from the curve for Planckian locus. This may cause, that the observer have the impression of a colour change despite minor changes of the colour temperature values. Due to the fact that the chromaticity points are locate near Planckian locus, the chromaticity difference can be assessed with the method according to the CIE 13.3-1995 [34]. As describe in chapter 2.1, the Macadam's ellipses may be replacement by circles of 0.0011 n radius. Variable n is a step number similar to the Macadam's ellipses. This method of evaluating the chromaticity change requires the CIE 1976 (u',v') chromaticity diagram. Two possible chromaticity variation limits are assumed, 3-step circle and 5-step circle. The centre of the circles is taken at the chromaticity point for the ECG lamp (Figure 7). If the chromaticity point is inside the 3-step circle the observer should not observe a change in light colour. All test lamps have a shifted chromaticity point after a ballast change outside the 3-step circle. Assuming less restrictive conditions for the chromaticity evaluation (5-step circle) for 100 W lamps only, this criterion is not met. The application of the n-step circle method of chromaticity change assessment does not give a measurable indicator to unequivocally determine the shift of the chromaticity point on the colour plane. The CIE 13.3-1995 [34] describes the chromaticity difference $\Delta_{u',v'}$, which is calculated from Formula (3). The calculated values of the chromaticity difference $\Delta_{u',v'}$ together with the chromaticity coordinates in the coordinate system (u',v') according to CIE 1976 are show in Table 1. Assuming that after changing ECG with EB the chromaticity coordinates should not change, the minimum value of this indicator $\min(\Delta_{u',v'})$ should be sought. The highest value of the chromaticity difference $\Delta_{u',v'}$ occurs for a 100 W lamp and is 0.0073. For the other lamps, it is similar and ranges from 0.0051 to 0.0056.

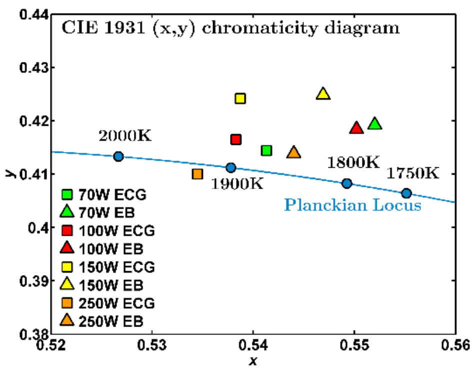


Figure 6. CIE 1931 chromaticity diagram with marked chromaticity points.

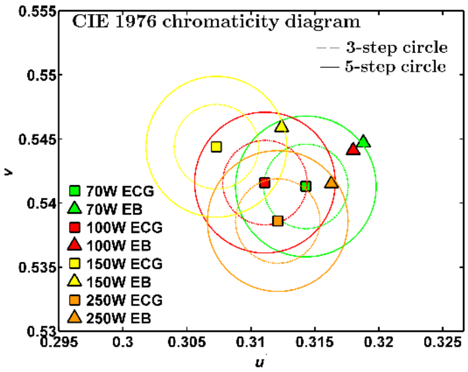


Figure 7. CIE 1976 chromaticity diagram with marked chromaticity points.

Table 1. Tristimulus coordinates values in the system u',v' CIE 1976and chromaticity difference $\Delta_{u',v'}$.

HPS Lamp		u'	v'	$\Delta_{u',v'}$
70 W	ECG	0.3143	0.5413	0.0056
	EB	0.3188	0.5447	
100 W	ECG	0.3111	0.5416	0.0073
	EB	0.3180	0.5441	
150 W	ECG	0.3073	0.5444	0.0053
	EB	0.3124	0.5459	
250 W	ECG	0.3121	0.5386	0.0051
	EB	0.3163	0.5415	

3.3. The Colour Rendering Index Analysis

The colour rendering index R_a (CRI) is determined during colorimetric measurements of light sources. It determines the colour rendering fidelity of the illuminated object by the light source under examination. Replacement of ECG with an electronic ballast should not worsen CRI. Therefore, assuming this assumption, the CRI value for HPS lamps with EB should not be lower than for HPS lamps with ECG. Based on the results of the chromaticity difference analysis present in the previous chapter, it can be assumed, that unfortunately CRI will deteriorate. This is confirmed by the measurement results shown in Figures 8–11. For all tested HPS lamps, the use of an electronic ballast causes a significant decrease in the R_a value. The biggest drop in R_a is for 70 W lamps. The smallest difference in R_a is observe for a 150 W lamp. Assuming that the R_a value for lamps with ECG is a reference value, the relative change in R_a for this case is 31.30%. It is more important to analyse not only the value of the total colour rendering index itself but also for which TCS these differences are greatest. According to the CIE guidelines, the R_a value is calculated as the average difference in colour perception of a given TCS when illuminated with test and reference light. The first 8 samples are, according to Munsell's atlas, characteristic low-saturation colours. Samples 9 to 12 are highly saturated characteristic colours. Sample 13 is the characteristic colour of human skin and sample 14 is the green colour of plant leaves.

The biggest changes of the CRI partial factor values for all tested lamps occur for R1, R4, R5, R12 and R13. For each of these TCS, there is a significant decrease in partial value. The biggest differences occur for TCS13 (R13), i.e., human skin colour. The replacement of the ballast may cause that an object of this colour, which is in the field of view, may be wrongly recognized by the observer. For the rest of the samples, changes of the partial factor values are less significant. For the yellow colour, which is an important element of e.g., warning signs, the deterioration of the colour rendering index is negligible. There is no reason to believe that the replacement of the ballast could be a potential source of deterioration of the recognition of a road signs by road users. There are also significant differences for TCS9, i.e., red—apart from 70 W HPS lamps. This is all the more important because during a traffic incident, emergency services may not correctly determine the extent and type of injury, but more importantly the colour of blood. In extreme cases, even the death of an injured person can be the cause of the wrong diagnosis of arterial blood.

On the basis of visual observation makes by the Authors, no differences in colour perception are found as large as the CRI values would suggest. In the Authors opinion, the method of its calculation has an impact on such a large reduction of R_a value. To sum up, without additional analysis of chromaticity difference based only on measured CRI values, incorrect conclusions can be formulated concerning the change of colorimetric parameters of HPS lamps after replacing ECG with EBs.

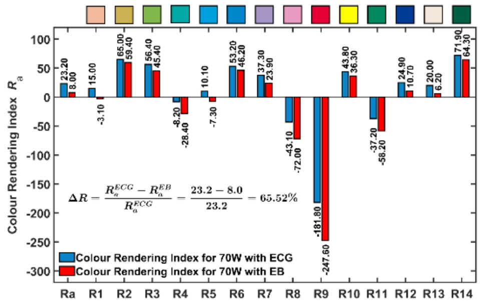


Figure 8. Comparison of R_a values for a 70 W lamp.

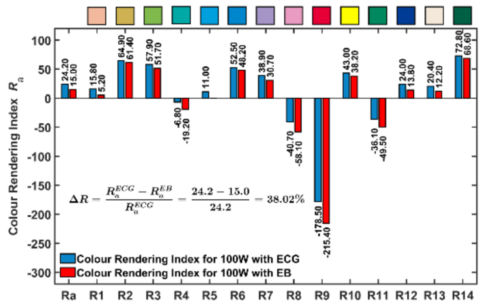


Figure 9. Comparison of R_a values for a 100 W lamp.

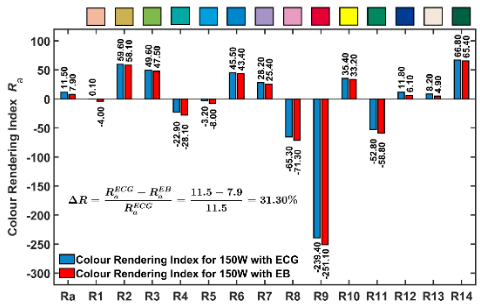


Figure 10. Comparison of R_a values for a 150 W lamp.

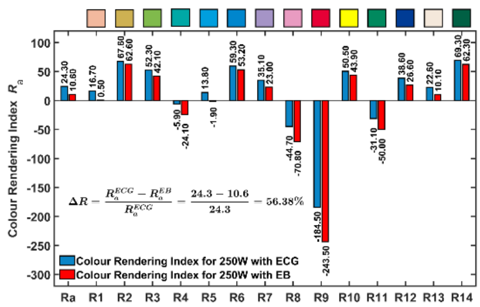


Figure 11. Comparison of R_a values for a 250 W lamp.

3.4. Results of ANSI/IES TM-30-15 Colour Rendering Analysis

The GLOptic Spectis 5.0 Touch application calculates colorimetric parameters in accordance with CIE guidelines as well as ANSI/IES TM-30-15. In this method two indicators are calculated: R_f colour fidelity and R_g colour gamut index. The measured values of these indicators are shown in Table 2. The table also shows the relative values of the change of R_f and R_g calculated using Formulas (7) and (8).

$$\Delta R_f = \frac{R_f^{\mathrm{ECG}} - R_f^{\mathrm{EB}}}{R_f^{\mathrm{ECG}}} \cdot 100\% \tag{7}$$

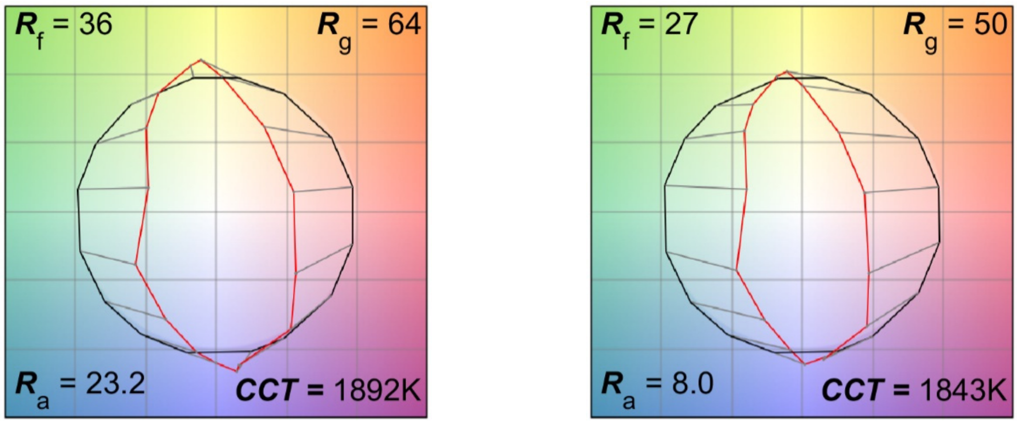
$$\Delta R_g = \frac{R_g^{\mathrm{ECG}} - R_g^{\mathrm{EB}}}{R_g^{\mathrm{ECG}}} \cdot 100\% \tag{8}$$

Table 2. Fidelity index and color index.

HPS Lamp		R_f	R_g	$\Delta_{R\mathrm{f},R\mathrm{g}}$	ΔR_f (%)	ΔR_g (%)
70 W	ECG EB	36 27	64 50	16.64	25.00	21.88
100 W	ECG EB	37 31	64 56	10.00	16.22	12.50
150 W	ECG EB	30 28	54 49	5.39	6.67	9.26
250 W	ECG	37	66	14.21	24.32	16.67
	EB	28	55			

For all tested HPS lamps, a decrease of the colour fidelity index and colour gamut index is observed. This indicates a change in hue fidelity as well as hue saturation. The biggest changes of R_f and R_g occurred for 70 W lamp. The replacement of the ballast causes a decrease of the R_f coefficient by 25.00% and of the R_g coefficient by 21.88%. The smallest changes of these indices are observed for a 150 W lamp. Here, these decreases are 6.67% for R_f and 9.26% for R_g, respectively.

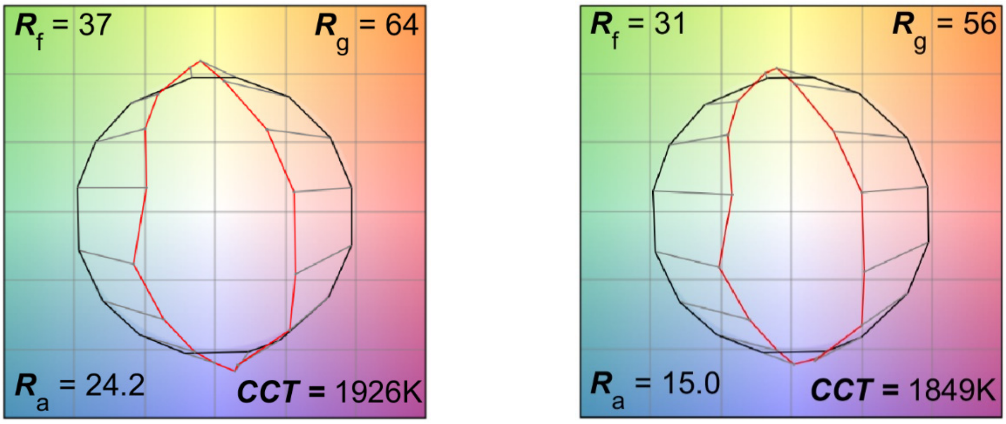
According to ANSI/IES TM-30-15, colour vector graphics (CVG) were also determined for HPS lamps with ECG and EB. The CVG determined for 70 W lamps is shown in Figure 12. Comparing the CVG obtained for this lamp, it can be stated that after converting ECG to EB there was a significant decrease in saturation but also a change in the colour tone.



(**a**) (**b**)

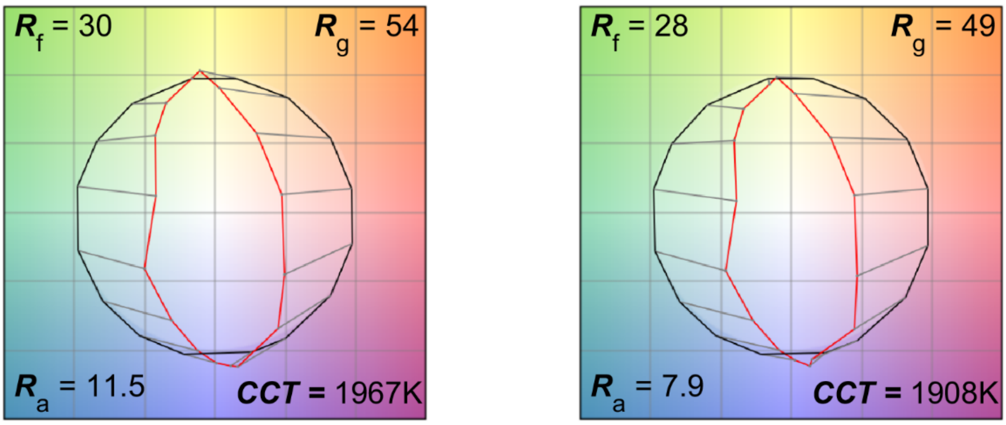
Figure 12. Colour vector graphics for 70 W HPS lamp with ECG (**a**) and EB (**b**).

Analysing the CVG obtained for 100 W HPS lamps (Figure 13a,b), there is also a noticeable decrease in saturation and colour change after changing ECG to EB. A similar phenomenon occurred for HPS lamps with nominal power of 150 and 250 W (Figures 14 and 15). Although for 250 W HPS lamps these changes are the smallest. On the basis of the CVG, without taking into account the numerical values, it is not possible to certain conclude to which state degree of change saturation and hue has occurred. This is more precisely determined by the R_f and R_g ratios discussed earlier. According to ANSI/IES TM-30-15, these indicators can be interpreted graphically by creating a graph of the R_f versus R_g dependence. For all tested HPS lamps, such graphs were made. They are shown in Figure 16a–d. The figures show the points corresponding to the variant when the HPS lamps is supplied by ECG and after its replacement with an electronic ballast. Shaded area (grey) approximating combinations that not classified as white light. The charts also indicate vectors describing the direction of changes in the relationship R_g versus R_f. The length of this vector $\Delta_{f,g}$, can be a measure of the change in colour rendering (fidelity and saturation of colour) and calculated using the Formula (5). The calculated values of $\Delta_{f,g}$ are presented in Table 2. As could be expected, the lowest value of $\Delta_{f,g}$ was obtained for 150 W HPS lamps ($\Delta_{f,g}$ = 5.39) and the highest for 70 W HPS lamps ($\Delta_{f,g}$ = 16.64). This indicator is a quantitative measure of colour rendering. Analysing the direction of displacement of R_g vs. R_f dependence points for all lamps, saturation and fidelity deteriorated after the ballast change. It can therefore be concluded that the colour rendering of lamps from EB is worse than when they were supplied by ECG.



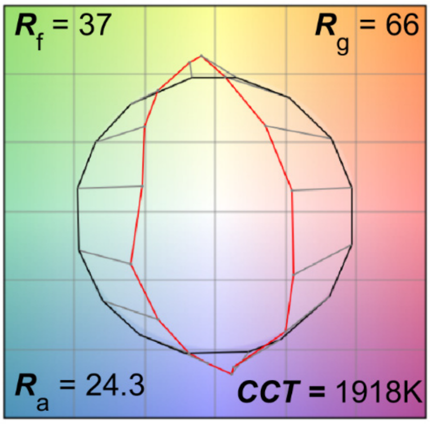
(**a**) (**b**)

Figure 13. Colour vector graphics for 100 W HPS lamp with ECG (**a**) and EB (**b**).

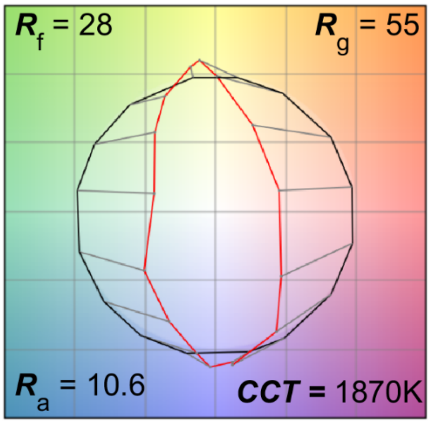


(**a**) (**b**)

Figure 14. Colour vector graphics for 150 W HPS lamp with ECG (**a**) and EB (**b**).

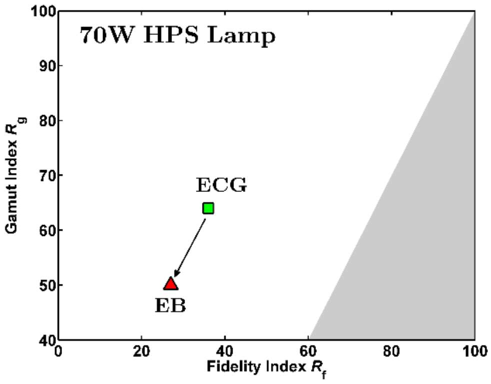


(a)

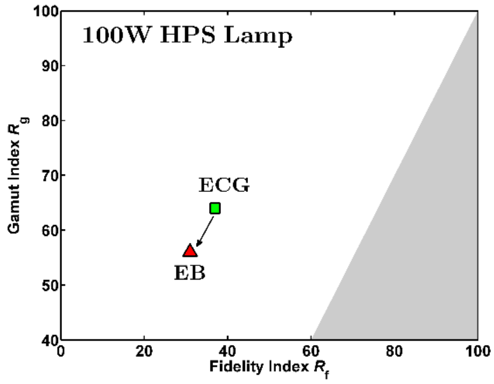


(b)

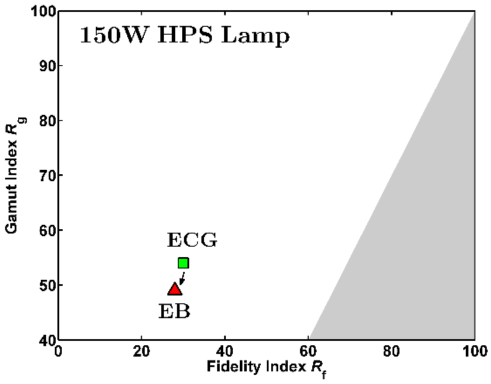
Figure 15. Colour vector graphics for 250 W HPS lamp with ECG (**a**) and EB (**b**).



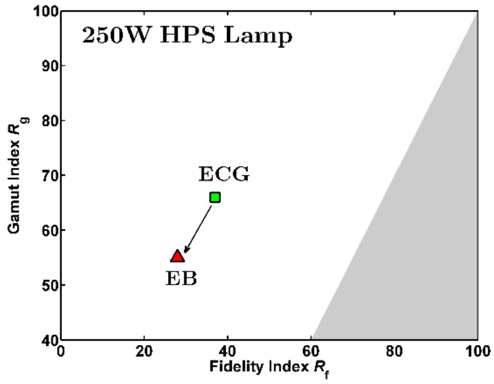
(a)



(b)



(c)



(d)

Figure 16. Values of R_g vs. R_f for: (**a**) 70 W HPS lamp, (**b**) 100 W HPS lamp, (**c**) 150 W HPS lamp, (**d**) 250 W HPS lamp.

Analysing the direction of displacement of R_g vs. R_f relation points for all lamps after changing the ballast, the saturation as well as fidelity deteriorated. It can therefore be concluded that the colour rendering of HPS lamps is worse than when they were supplied by ECG.

4. Discussion

The paper presents the results of comparative analysis of colorimetric parameters of HPS lamps with electromagnetic control gear and after its replacement with electronic ballast. The electronic ballast used in the research reduces the power of the lamp and thus the electricity consumption. Usually, the reduction of the active power is the same as the reduction of luminous flux, which in turn indicates a reduction of lamp radiation power. The article presents the influence of the change of ECG to EB on the SPD value. On the basis of the obtained results, it can be concluded that the radiation power has been reduced for all wavelengths. These changes are not linear for all wavelengths and the reduction of radiation power is greater than it would result from the reduction of luminous flux.

The analysis of colorimetric parameters is performed by two methods: CIE TN 001:2014 [46] and ANSI/IES TM-30-15 [47]. Spectrometric measurements show, that after changing the ECG to EB colour temperature do not change significantly. For all tested lamps this change do not exceed 5%. Chromaticity points for HPS lamps with ECG and EB are plotted on CIE 1931 diagram. These points are located near Planckian locus. This gives the possibility to apply the method of evaluating the chromaticity change according to CIE TN 001:2014 [46]. For the evaluation n-step circle for $n = 3$ and $n = 5$ is used. Apart from the 150 W lamp, the chromaticity points were inside the 5-step circle. The chromaticity difference is also calculated according to CIE TN 001:2014 [46]. The obtained measure of the chromaticity point shift gives information about the value of the chromaticity change but does not give information about the influence on saturation and fidelity. The change of R_a value is interesting. For all lamps this change is large (in the range from 30% to 70%), which leads to the conclusion that the colour rendering has been greatly deteriorated. Although the observed light colour of the lamp and its measured colour temperature do not suggest such big changes. Such big differences in R_a value can be caused by the method of its calculation. It is based only on partial R_i values for the first 8 TCS and does not take into account other samples. For this reason, the analysis of colorimetric parameters is performed in accordance with ANSI/IES TM-30-15 [47]. In this method two colour fidelity R_f and colour gamut R_g indicators are determined. The calculated differences for these indices for HPS lamps with ECG and EB are much smaller than for R_a. The method by which these indices are calculated is based on 99 colour samples and uses other reference sources. Although the colour vector graphics illustrates fidelity and saturation changes in a simple way, its interpretation requires attention and knowledge. From a practical point of view one indicator is needed, which numerically describes the change in fidelity and saturation, analogous to the chromaticity difference according to CIE TN 001-2014. Based on the R_g vs. R_f graph, on which points corresponding to the values obtained for a given light source are applied, it is possible to introduce an indicator describing the displacement of a point as a result of e.g., a change in supply voltage parameters or dimming. The displacement can be described as a vector whose length is a measurable value of fidelity and saturation change. The introduction of the vector facilitates interpretation by showing the direction of fidelity and saturation changes.

Analysing the R_f (IES) dependence as a function of the R_a (CIE) value, it can be concluded that it is practically linear. The R_f values obtained for all tested lamps are greater than the R_a values. This leads to the conclusion that the effect on the colour rendering of HPS lamps after the change of ECG to EB is not as great as suggested by R_a (Figure 17).

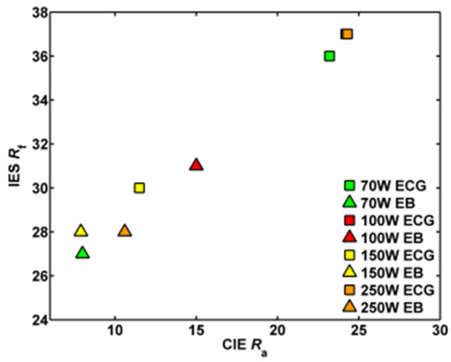


Figure 17. Relationship IES R_f versus CIE R_a.

Additionally, the active power of HPS lamps was measured, when HPS lamp was supplied by ECG and after replacement with EB. Comparing Figures 4 and 18, it can be concluded that the percentage change in the luminous flux value does not correspond to the percentage change in active power. For 70, 100 and 250 W lamps the luminous flux reduction is greater than the active power reduction. For a 150 W lamp, the luminous flux is decreased more than the active power. Additionally, on the basis of the measured luminous flux and active power values, the luminous efficacy of HPS lamps with ECG and EB is calculated. It is calculated as the quotient of the luminous flux and the active power. In addition to the 250 W lamp for the three other lamps, the luminous efficacy is decreased, as shown in Figure 19. The impact of replacing ECG by EB on electrical parameters is described in Appendix A.

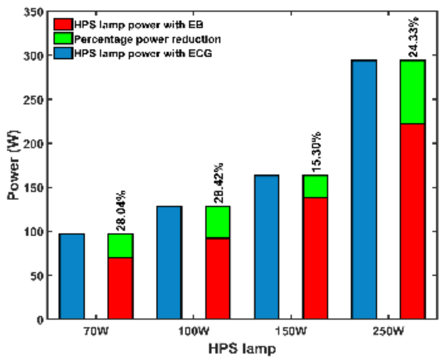


Figure 18. Comparison of HPS active power of lamps with ECG and EB.

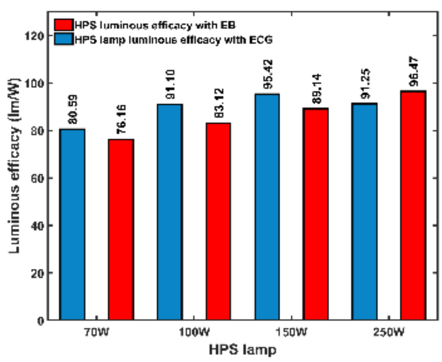


Figure 19. Comparison of HPS luminous efficacy of lamps with ECG and EB.

Colour rendering is important not only for indoor lighting but also for outdoor lighting. The perception of colour is a subjective impression. This ability may vary from one observer to another. From a technical point of view, however, it is important to develop a method that will allow to describe this phenomenon by means of mathematical dependencies as it is in [46]. Currently, research works are being carried out to develop new measurable indicators describing the phenomenon of colour rendering of light sources [49,50].

5. Conclusions

Luminaires for high-pressure sodium lamps are still widely used in road lighting despite the clear growth of modern LED-based luminaires. To improve functionality and energy efficacy, electronic ballasts are used instead of magnetic ballasts, e.g., when modernising an existing lighting installation. Replacement of the ballast shall not deteriorate the colorimetric, photometric or electrical parameters of the HPS lamps. Although LED technology is developing dynamically, luminaires for high-pressure sodium lamps are and will continue to be used in road lighting for a long time. The need to improve energy efficiency and the addition of new functionalities to the installation (control according to the assumed schedule) forces the use of electronic ballasts. This must not be done at the expense of reducing road safety. It depends, among others, on the colour rendering index of the light sources used. The paper reviews the methods of evaluating this coefficient together with a proposal to introduce new indicators to supplement the existing ones.

The methods described in CIE and ANSI/IES TM-30-15 documents were used for the assessment. The paper presents the results of a detailed analysis of the influence of ECG replacement with the electronic ballast, mainly on colorimetric and photometric parameters. For lamps supplied by electronic ballast, a decrease of the spectral power density for selected wavelengths has been observed, greater than that resulting from the reduction of luminaire luminous flux implemented in the control algorithm. Therefore, the analysis is made on the basis of measurements made for four high-pressure sodium lamps of 70, 100, 150 and 250 W. The measurements are made for lamps supplied by ECG, which are then replaced by electronic ballasts dedicated for these lamps. Several known evaluation methods are chosen to assess the change of colorimetric parameters of lamps. The analysis of chromaticity point change in the colour plane when changing the ballast is small and at the same time does not give a measurable indicator of these changes. When comparing the total colour rendering index R_a, a change of the ballast causes its drastic decrease from already small value 23 to only 8. The reason for such a significant change of this index results from the way it is determined and in this situation the change of R_a value may not give reliable results. Completely different conclusions can be drawn by analysing changes in colour temperature. A change of the ballast from magnetic to electronic does not noticeably affect its change. The differences obtained in its values suggest, that they are not noticed by the observer.

In the opinion of the Authors, the IES TM-30-15 method provides more accurate results than the CIE method. The method is based on determining two indicators: colour fidelity R_f and colour gamut R_g. The calculated differences for these indicators for HPS lamps with ECG and EB are much smaller than for R_a. Using an electronic ballast reduces their values by up to 25% which seems to be the most reliable result. It has been proposed to introduce the $\Delta_{f,g}$ indicator which determines the change of colorimetric parameters based on fidelity and gamut colour indicator. Using this indicator to assess the change of the chromaticity point positions allows for a quantitative analysis of the effects of replacing ECG to EB.

Author Contributions: Conceptualization, R.S., P.M.; data curation, R.S. and P.M.; formal analysis, R.S. and P.M.; methodology, R.S. and P.M.; writing—original draft, R.S. and P.M.; and writing—review and editing, R.S. and P.M. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Conflicts of Interest: The authors declare no conflict of interest.

Appendix A

Table A1 presents the measured values of electrical parameters, luminous flux Φ and the calculated value of luminous efficacy η. The luminous efficacy was calculated as the quotient of the luminous flux and the active power. According to the declaration of the electronic ballast manufacturer, the active power P consumed by the ballast-lamp system is practically equal to the power of the lamp (less in the case under consideration) with a 5% tolerance. All ECGs were equipped with a capacitor to compensate the inductive reactive power. In the case of a 250 W lamp with ECG, the capacitor capacitance value was too high so the reactive power Q has a capacitive character. In Table A1 a minus sign indicates the capacitive character. The other analysed HPS lamps with ECG have inductive character. The replacement of ECG by EB resulted in an increase of reactive power, only for 250 W lamp there was a decrease in reactive power, and a change of character from inductive to capacitive. The power factor values of PF_{DD} displacement and distortion PF_{DD} tested lamps with ECG and EB have values close to 1. Analysing the measured values of THD_I (Total Harmonic Distortion) current, it can be concluded that the replacement of ECG by EB reduced the value of THD_I in all considered cases. The greatest reduction of THD_I value was observed for a 100 W HPS lamp. The THD_I value for a lamp with ECG is 4.92 times higher than for a lamp with EB. The replacement of ECG with EB also reduces the luminous flux values Φ. The smallest luminous flux reduction occurred for 250 W HPS lamps and was 20.00% and the largest for 100 W HPS lamps—34.68%. Luminous efficacy has also been reduced with the exception of 250 W HPS lamps. The use of EB in the case of this lamp has increased the lamp luminous efficacy. For each of the tested lamps, the change of luminous efficacy did not exceed 10%.

Table A1. Electrical parameters, luminous flux and luminous efficacy of HPS lamps with ECG and EB.

Lamp		P (W)	Q (var)	I (A)	PF_D	PF_{DD}	THD_I (%)	Φ (lm)	η (lm/W)
70 W	ECG	96.92	1.88	0.43	0.999	0.978	20.56	7775	80.59
	EB	69.74	−14.98	0.31	−0.978	−0.976	6.35	5311	76.16
100 W	ECG	128.76	11.31	0.58	0.996	0.996	24.83	11728	91.10
	EB	92.17	−14.40	0.41	−0.988	−0.987	5.05	7661	83.12
150 W	ECG	163.47	23.97	0.73	0.989	0.973	18.11	15595	95.42
	EB	138.44	−11.13	0.61	−0.997	−0.996	4.36	12340	89.14
250 W	ECG	294.10	−19.34	1.31	−0.998	−0.976	20.42	26838	91.26
	EB	222.56	−11.39	0.98	−0.999	−0.994	8.48	21471	96.47

Table A2 summarizes the percentage values of the higher current harmonics of the tested HPS lamps with ECG and EB. As could have been expected, the use of EB reduced the values of harmonic orders from 3 to 11. The greatest reduction was observed for harmonics order 3.

Table A2. HPS lamp current harmonics with ECG and EB.

Lamp		I_3 (%)	I_5 (%)	I_7 (%)	I_9 (%)	I_{11} (%)	I_{13} (%)	I_{15} (%)	I_{17} (%)	I_{19} (%)	I_{21} (%)	I_{23} (%)	I_{25} (%)	I_{27} (%)	I_{29} (%)
70 W	ECG	19.63	4.63	3.37	1.49	0.97	0.62	0.31	0.30	0.14	0.11	0.10	0.09	0.07	0.07
	EB	5.46	1.26	0.95	0.89	0.82	0.70	0.58	0.55	0.42	0.45	0.28	0.26	0.48	0.32
100 W	ECG	24.11	3.98	3.77	1.64	1.08	0.73	0.40	0.37	0.19	0.21	0.15	0.13	0.25	0.09
	EB	4.41	1.28	0.53	0.17	0.10	0.23	0.45	0.41	0.26	0.29	0.19	0.32	0.21	0.43
150 W	ECG	17.20	4.18	3.30	1.28	0.90	0.59	0.27	0.31	0.15	0.11	0.14	0.13	0.13	0.13
	EB	3.81	1.29	0.78	0.59	0.45	0.19	0.13	0.33	0.35	0.29	0.18	0.08	0.06	0.13
250 W	ECG	19.30	5.17	3.44	1.75	1.21	0.75	0.43	0.43	0.21	0.24	0.17	0.13	0.20	0.05
	EB	6.99	0.64	2.70	2.07	0.60	1.84	1.24	0.45	0.99	0.95	0.47	0.89	1.08	0.42

References

1. Kostic, M.; Djokic, L. Recommendation for energy efficient and visually acceptable street lighting. *Energy* **2009**, *34*, 1565–1572. [CrossRef]
2. Campisi, D.; Gitto, S.; Morea, D. Economic feasibility of energy improvements in street lighting systems in Rome. *J. Clean. Prod.* **2018**, *175*, 190–198. [CrossRef]
3. Lecce, F.; Salvadoni, G.; Rocca, M. Critical analysis of the energy performance indicators for road lighting systems in historical towns of central Italy. *Energy* **2017**, *138*, 616–628. [CrossRef]

4. Beccali, M.; Bonomolo, M.; Leccese, F.; Lista, D.; Salvadoni, G. On the impact of safety requirements, energy prices and investment costs in street lighting refurbishment design. *Energy* **2018**, *165*, 739–759. [CrossRef]
5. Silva, J.; Mendes, J.F.G.; Silva, L.T. Assesment of energy efficiency in street lighting design. *WIT Trans. Ecol. Environ.* **2010**, *129*, 705–715.
6. Boyce, P.R.; Fotios, S.; Richards, M. Road lighting and energy savings. *Light. Res. Technol.* **2009**, *41*, 245–260. [CrossRef]
7. Beccali, M.; Bonomolo, M.; Ciulla, G.; Galatioto, A.; Lo Brano, V. Improvement of energy efficiency and quality of street lighting in South Italy as an action of Sustainable Energy Action Plans. The case study of Comiso (RG). *Energy* **2015**, *92*, 394–408. [CrossRef]
8. Djuretic, A.; Kostic, M. Actual energy savings when replacing high-pressure sodium with LED luminaires in street lighting. *Energy* **2018**, *157*, 367–378. [CrossRef]
9. Orzáez, M.J.H.; de Andrés Díaz, J.R. Comparative study of energy-efficiency and conservation systems for ceramic metal-halide discharge lamps. *Energy* **2013**, *52*, 258–264. [CrossRef]
10. Orzáez, M.J.H.; Róchaz Sola, J.; Gago-Calderon, A. Electrical consequences of large-scale replacement of metal-halide by LED luminaires. *Light. Res. Technol.* **2016**, *50*, 282–293. [CrossRef]
11. The Energy Efficiency Directive (2012/27/EU). Available online: https://eur-lex.europa.eu/legal-content/EN/TXT/HTML/?uri=CELEX:32012L0027&from=EN (accessed on 1 February 2020).
12. EU 2020 Target for Energy Efficiency. Available online: https://ec.europa.eu/energy/topics/energy-efficiency/targets-directive-and-rules/eu-targets-energy-efficiency_en?redir=1 (accessed on 1 February 2020).
13. European Commission. Commission Delegated Regulation No 874/2012 of 12 July 2012 Supplementing Directive 2010/30/EU of the European Parliament and of the Council with Regard to Energy Labelling of Electrical Lamps and Luminaires. 2012. Available online: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A32012R0874 (accessed on 1 February 2020).
14. European Commission. Commission Regulation (EC) No 347/2010 of 21 April 2010 Amending Commission Regulation No 245/2009 as Regards the Ecodesign Requirements for Fluorescent Lamps without Integrated Ballast, for High Intensity Discharge Lamps, and for Ballasts and Luminaires Able to Operate Such Lamps. 2010. Available online: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A32010R0347 (accessed on 1 February 2020).
15. European Commission. Commission Regulation (EC) No 245/2010 of 18 March 2009 Implementing Directive 2005/32/EC of the European Parliament and of the Council with Regard the Ecodesign Requirements for Fluorescent Lamps without Integrated Ballast, for High Intensity Discharge Lamps, and for Ballasts and Luminaires Able to Operate Such Lamps and Repealing Directive 2000/55/EC of the European Parliament and of the Council. 2009. Available online: https://eur-lex.europa.eu/legal-content/en/TXT/?uri=CELEX%3A02009R0245-20100413 (accessed on 1 February 2020).
16. European Commission. Commission Regulation (EC) No 1194/2012 of 12 December 2012 Implementing Directive 2009/125/EC of the European Parliament and of the Council with Regard the Ecodesign Requirements for Directional Lamps, Light Emitting Diode Lamps and Related Equipment. 2012. Available online: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A32012R1194 (accessed on 1 February 2020).
17. European Commission. Directive 2011/65/EU of the European Parliament and the Council of 8 June 2011 on the Restriction of the Use of Certain Hazardous Substances in Electrical and Electronic Equipment. 2009. Available online: https://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2011:174:0088:0110:EN:PDF (accessed on 1 February 2020).
18. EN 13201-5:2015. *Light and Lighting. Road Lighting–Part 5: Energy Performance Indicators*; International Electrical Commission: Dublin, Ireland, 2015.
19. Yoomak, S.; Jettansen, C.; Ngaopitakkul Bunjongjit, S. Comparative study of lighting quality and power quality for LED and HPS luminaires in a roadway lighting system. *Energy Build.* **2018**, *159*, 542–557. [CrossRef]
20. Mayeur, A.; Bremond, R.; Bastien, J.C. The effect of the driving activity on target detection as a function of the visibility level: Implications for road lighting. *Transp. Res.* **2010**, *13*, 115–128. [CrossRef]
21. Boomsma, C.H.; Steg, L. The effect of information and values on acceptability of reduced street lighting. *J. Environ. Psychol.* **2014**, *39*, 22–31. [CrossRef]
22. Pena-Garcia, A.; Hurtado, A.; Aguilar-Luzon, M.C. Impact of public lighting on pedestrians' perception of safety and well-being. *Saf. Sci.* **2015**, *78*, 142–148. [CrossRef]

23. Bullough, J.D.; Donnell, E.T.; Rea, M.S. To illuminate or not to illuminate: Roadway lighting as it affects traffic safety at intersections. *Accid. Anal. Prev.* **2013**, *53*, 65–77. [CrossRef]
24. Anarkooli, A.J.; Hosseinlou, M.H. Analysis of the injury severity of crashes by considering different lighting conditions on two-lane rural roads. *J. Saf. Res.* **2016**, *56*, 57–65. [CrossRef]
25. Jackett, M.; Frith, W. Quantifying the impact of road lighting on road safety-a New Zealand study. *IATSS Res.* **2013**, *36*, 139–145. [CrossRef]
26. Kircher, K.; Ahlstrom, C. The impact of tunnel design and lighting on the performance of attentive and visually distracted drivers. *Accid. Anal. Prev.* **2012**, *47*, 153–161. [CrossRef]
27. Fryc, I.; Fryc, J.; Wąsowski, K. Rozważania o jakości oddawania barw źródeł światła, wyrażanej wskaźnikiem Ra (CRI) uwzględniające fizjologię widzenia oraz zagadnienia techniczno–prawne. *Przegląd Elektrotechniczny* **2016**, *92*, 218–223. [CrossRef]
28. Tabaka, P.; Rozga, P. Assessment of methods of marking LED sources with the power of equivalent light bulb. Bull. *Polish Acad. Sci. Technol. Sci.* **2017**, *65*, 883–890. [CrossRef]
29. Tabaka, P.; Rozga, P. The light color quality of LEDs operating at winter temperatures. *Photonics Lett. Pol.* **2019**, *11*, 112–114. [CrossRef]
30. Chen, Y.S. Anti-glare LED lamps with adjustable illumination light field. *Opt. Express* **2014**, *22*, 5183–5195. [CrossRef]
31. Ye, Z.T. Hollow Light Guide Module Involving Mini Light-Emitting Diodes for Asymmetric Luminous Planar Illuminators. *Energies* **2019**, *12*, 2755. [CrossRef]
32. Huang, Y.S. How smart LEDs lighting benefit color temperature and luminosity transformation. *Energies* **2017**, *10*, 518. [CrossRef]
33. Tabaka, P.; Rozga, P. Influenece of a light source installed in a luminaire of opal sphere type on the effect of light pollution. *Energies* **2020**, *13*, 306. [CrossRef]
34. Commission Internationale de l'Eclairage. *Method of Measuring and Specifying Colour Rendering Properties of Light Sources: Technical Report: CIE 13.3-1995*; International Commission on Illumination: Vienna, Austria, 1995.
35. Yaguchi, H.; David, A.; Fuchida, T.; Hashimoto, K.; Heidel, G.; Jordan, W.; Jost-Boissard, S.; Kobayashi, S.; Kotani, T.; Luo, R.; et al. CIE 2017 Colour Fidelity Index for Accurate Scientific Use; cie224; International Commission on Illumination. 2017. Available online: https://www.researchgate.net/publication/316472507_CIE_2242017_CIE_2017_Colour_Fidelity_Index_for_accurate_scientific_use_httpwwwciecoatindexphpi_ca_id1027 (accessed on 1 February 2020).
36. *CIE C. 15: 2004 Colorimetry*; Central Bureau of the CIE: Vienna, Austria; International Commission on Illumination: Washington, DC, USA, 2004.
37. Djuretic, A.; Kostic, M. Comparison of electronic and conventional ballasts used in roadway lighting. *Lighting Res. Technol.* **2014**, *46*, 407–420. [CrossRef]
38. Omar, M.H.; Abdul Rahman, H.; Majid, M.S.; Hassan, M.Y.; Rosmin, N. The Reduction of Total Harmonic Distortion and Electromagnetic Interference in High Pressure Sodium Street Lighting Using Single Stage Electronic Ballast. In Proceedings of the 2012 IEEE International Power Engineering and Optimization Conference, Melaka, Malaysia, 6–7 June 2012. [CrossRef]
39. Mansour, A.A.; Arafa, O.A. Comparative study of 250 W high pressure sodium lamp operating from both conventional and electronic ballast. *J. Electr. Syst. Inf. Technol.* **2014**, *1*, 234–254. [CrossRef]
40. Nsibi, W.; Nehdi, M.; Chammam, A.J.; Sellami, A.; Zissis, G. Dimmable Electronic Ballast for HPS Lamp Operating in LF. In Proceedings of the 7th International Renewable Energy Congress (IREC), Hammamet, Tunisia, 22–24 March 2016. [CrossRef]
41. Nehdi, M.N.; Nsibi, W.; Chammam, A.; Sellami, A.; Zissis, G. Frequency dimmable electronic ballast for a 250W HPS lamp. In Proceedings of the 7th International Renewable Energy Congress (IREC), Hammamet, Tunisia, 22–24 March 2016. [CrossRef]
42. Shu-Hung Chung, H.; Ho, N.M.; Yan, W.; Tam, P.W.; Hui, S.Y. Comparison of Dimmable Electromagnetic and Electronic Ballast Systems—An Assessmenton Energy Efficiency and Lifetime. *IEEE Trans. Ind. Electron.* **2007**, *54*, 3145–3154. [CrossRef]
43. Omar, M.H.; Rahman, H.A.; Majid, M.S.; Rosmin, N.; Hassan, M.Y.; Wan Omar, W.Z. Design and simulation of electronic ballast performance for high pressure sodium street lighting. *Light. Res. Technol.* **2013**, *45*, 729–739. [CrossRef]

44. Hosseini, S.H.; Sabahi, M.; Goharrizi, A.Y. An improved topology of electronic ballast with wide dimming range, PFC and low switching losses using PWM-controlled soft-switching inverter. *Electr. Power Syst. Res.* **2008**, *78*, 975–984. [CrossRef]
45. Burgio, A.; Menniti, D. A novel technique for energy savings by dimming high pressure sodium lamps mounted with magnetic ballasts using a centralized system. *Electr. Power Syst. Res.* **2013**, *96*, 16–22. [CrossRef]
46. Ohno, Y.; Blattner, P. *Chromaticity Difference Specification for Light Sources*; International Commission on Illumination, Tech. Rep. CIE TN: 2014; International Commission on Illumination: Vienna, Austria, 2014; Volume 1.
47. Illuminating Engineering Society of North America. *IES Method for Evaluating Light Source Color Rendition*; IES TM-30-15; Illuminating Engineering Society: New York, NY, USA, 2015.
48. Hyodhyad, K.; Supanaroj, K. Energy Saving Project for Street Lighting of Provincial Electricity Authority (PEA). In Proceedings of the International Conference on Energy and Sustainable Development: Issues and Strategies (ESD 2010), Chiang Mai, Thailand, 2–4 June 2010. [CrossRef]
49. Hashimoto, K.; Yano, T.; Shimizu, M.I.; Nayatani, Y. New method for specifying color-rendering properties of light sources based on feeling of contrast. *Color Res. Appl.* **2007**, *32*, 361–371. [CrossRef]
50. Rea, M.S. (Ed.) *IESNA Lighting Handbook: Reference and Application*, 9th ed.; Illuminating Engineering Society of North America: New York, NY, USA, 2000.