A New Approach to Power Consumption Reduction of Street Lighting

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Keywords: Street Lighting, Ambient Light, EN 13201, PhoCa.

Abstract: Annual energy costs of streetlighting power usage are expected to reach \$23.9 billion to \$42.5 billion by 2025. Those numbers encourage us to search any methods reducing energy consumption. In this article we propose a new approach to achieving power savings. The approach is based on combining *daylight harvesting* methodology and lighting class reduction. Its novelty relies on the analytically determined adjusting of fixtures' dimming levels which ensures the compliance with mandatory lighting standard. In the article we show appropriate test cases and give quantitative results of applying the proposed method.

1 INTRODUCTION

According to the 2014 report published by Northeast Group over 280 million streetlights are installed in the world and this number is estimated to reach nearly 340 million by 2025. Assuming that each of those lighting points uses 600 to 1,000 kWh/yr (which gives annually \$70 to \$125 per lamp, assuming the rate \$0.12/kWh) we expect the annual energy costs to reach \$23.9 billion to \$42.5 billion by 2025 (Whitepaper by Echelon, 2015). In these circumstances each optimization of the power usage brings significant money savings.

One of the technological results of the growing share of LED light sources in the outdoor lighting market is development of solutions based on LED's crucial properties: very low onset time (measured in nanoseconds) and their full dimmability (i.e., in the range 0-100%). Those solutions allow for decreasing power consumption by fitting an installation performance to actual needs.

The common approach to implementing power saving installations is applying schedules which precise what power should be supplied to lamps in particular periods of the day (see Section 2). Those schedules are based on statistical data for a given road.

To fully benefit LEDs capabilities, however, a lighting system has to cooperate with a telemetry layer containing appropriate sensors (movement, presence, induction loops and so forth) reporting an actual environment state.

Such solutions may be successfully implemented in areas where the safety, in terms of road accidents rate, is not the critical factor, e.g., in parks or pedestrian walkways. In those cases lighting installation performance may be adjusted immediately to changing conditions, e.g., due to people entering or leaving a given area.

In the case of roads we deal with legal issues related to the traffic safety. In those circumstances a lighting system performance can not follow environment changes instantly but needs to be adjusted with some delay to ensure that these changes are not temporary: if changes persist in a given time window (e.g., 15 minutes long) then the performance may be adjusted accordingly. PhoCa software system complying with the above requirement will be considered here (Kotulski et al., 2013). This program is capable of performing bulk photometric computations and efficient solution finding.

2 ENERGY SAVING STRATEGIES

Planing investments oriented for the reduction of illumination costs one has to take into account various factors: business, technological and standard-related ones. Economic goals may include payback period, net present value (NPV), maintenance costs, investment costs and many others. Since those objectives are strongly case-dependent we do not consider them here.

The lighting standard-related aspect concerns the mandatory compliance of an installation with regula-

SÈľdziwy A. and Kotulski L..
A New Approach to Power Consumption Reduction of Street Lighting.
DOI: 10.5220/0005479702830287
In *Proceedings of the 4th International Conference on Smart Cities and Green ICT Systems* (SMARTGREENS-2015), pages 283-287
ISBN: 978-989-758-105-2

Table 1: ME lighting classes according to EN 13201:2. Performance requirements: L_{avg} – minimum average luminance, U_o, U_l – minimum uniformities (overall and longitudinal), TI – maximum threshold increment, SR – minimum surround ratio.

Class	L_{avg} cd/m^2	U$_o$	U$_l$	$TI[\%]$	SR
ME1	2.0	0.4	0.7	10	0.5
ME2	1.5	0.4	0.7	10	0.5
ME3a	1.0	0.4	0.7	15	0.5
ME3b	1.0	0.4	0.6	15	0.5
ME3c	1.0	0.4	0.5	15	0.5
ME4a	0.75	0.4	0.6	15	0.5
ME4b	0.75	0.4	0.5	15	0.5
ME5	0.5	0.35	0.4	15	0.5
ME6	0.3	0.35	0.4	15	-

tions specifying its performance and thus the generated lighting conditions. There are various standards regulating those issues: CIE 115 (Commission Internationale de l'Eclairage, 2010), EN 13201, IESNA RP-8-00 (Illuminating Engineering Society of North America (IESNA), 2000). In this paper we will follow the European norm EN 13201:2 (Table 1, (Standardization, 2003a)) defining performance requirements for road lighting.

The first approach to the reduction of illumination costs is a simple retrofit of a lighting installation, i.e., the replacement of existing fixtures with more efficient ones. Let us consider as an example the replacement of metal halide (MH) fixtures by LED sources. Due to the higher luminous efficacy of LEDs such the replacement may yield the significant reduction of the power usage. To illustrate this we analyze the two-lane carriageway (width $w = 7m$) of the lighting class ME4a (according to EN 13201-2, (Standardization, 2003a)) with the single sided right lamp arrangement (lamp spacing $s = 39m$, mounting height $H = 10m$, fixture overhang $d = 0.5m$ and inclination $\alpha = 5°$) with surface given by R-Table R3 and $Q_0 = 0.07$. Suppose that initially the MH fixture `SGS253 GB CR P5X` is mounted along the road. Then we replace it with the LED one, namely `BGP353 T15 DN GRN104`, in such a way that the performance requirements for ME4a class remain satisfied. Neglecting the reactive power we may find the relative power reduction $\Delta = \frac{P_{MH} - P_{LED}}{P_{MH}} \times 100\%$, which is equal to 51.1% (see Table 2).

The next step after deploying LEDs is adjusting their luminous flux (by reducing the supplied power) to the lowest level which guaranties meeting ME4a requirements. For the above example the initial luminous flux (and power, which is assumed to be coupled linearly with luminous flux) may be reduced by 21%.

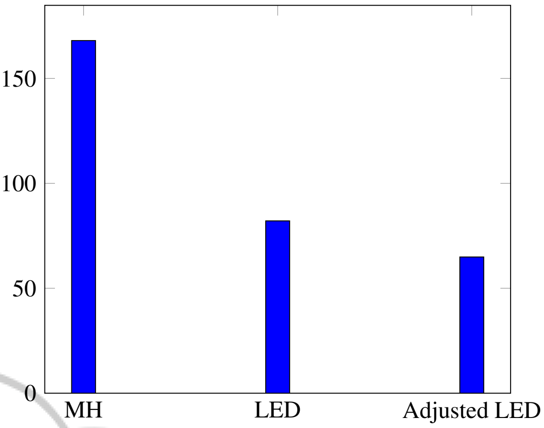

Figure 1: Power usages.

Table 2: Fixture type replacement: MH = `SGS253 GB CR P5X`, LED = `BGP353 T15 DN GRN104`. $^{\star)}$ dimmed by 21%.

	L_{av} $[\frac{cd}{m^2}]$	U_o	U_l	TI $[\%]$	SR $[\%]$	P $[W]$
MH	0.81	0.63	0.60	8.0	68	168
LED	0.95	0.62	0.78	9.6	62.4	82.1
LED*	0.75	0.62	0.78	9.1	62.4	64.9*

Summarizing above steps we reduced the power usage by 61.4% (see Figure 1).

Further steps towards a cost minimizing lighting installation are related to control systems. Note that the control may be realized at the various levels of a technical advancement. Primarily, all installations work according to the astronomical clock which turns lamps on and off at times dependent on a geographic location and a current day of the year. In the basic scenarios control is performed by using predefined work schedules which specify dimming levels in particular hourly intervals. This method is commonly used in numerous commercial street lighting systems (e.g., Owlet, LightGrid, CityTouch).

Yet another method of energy saving referred to as Constant Lumen Output, is changing power supply scheme. The typical approach to compensation of the light loss caused by lamp aging is supplying constant (over the time), raised power level so that at the end of a fixture's life cycle the lumen output keeps meeting the performance requirements. The alternative and cost saving method assumes that the power level will be increased continuously during the fixture's lifetime in such a way that in every moment the lumen output meets requirements with no superfluous power usage.

3 COMBINED METHOD

In the further considerations we will focus on the method being a compound of two approaches. The first one is *daylight harvesting* which is applicable in twilight periods, when some level of natural ambient light is present and impacts a street illuminance. The second approach is based on lighting class reduction which is made when a car traffic decreases.

Applying the combination of the artificial and natural ambient light is not only the subject of multiple researches (Joshi et al., 2013; Long et al., 2009; Archana and Mahalahshmi, 2014) but is also practically used in the intelligent lighting systems (OSRAM, 2015). This usage is not supported, however, by the reliable quantitative assessment of the resultant lighting conditions. For that reason it is not known if the lighting performance requirements are satisfied when those two types of light are considered together.

In this section we explain how the ambient illuminance may be introduced to photometric equations. We also give the formal framework for the ambient light-aware control.

3.1 Ambient Light Injection

It is assumed that a level of daylight illuminance may be measured using ambient light sensors and thus included in photometric computations (Standardization, 2003b; Kotulski et al., 2013). Next, the effective illuminance will be determined as a superposition of the natural ambient light and an artificial one. From the perspective of photometric computations it requires modifying the illuminance formula and all derivative formulas (luminance, threshold increment, surround ratio and so on) by injecting luminous intensity of the ambient light (measured by sensors) to the above ones.

To avoid obtaining non-physical results of photometric computations one has to take into account some properties of the ambient light (abbrev. AL) and make some assumptions:

1. In the further considerations we assume the fully overcast sky and thus the perfectly diffused light: ambient light.
2. AL is isotropic, i.e., it's value measured by a sensor doesn't depend on an observation angle. We may make such an assumption because the AL is not emitted by a point light source but the entire sky area.
3. AL is constant in the sense that it doesn't change with a distance. The actual source of the AL is the Sun and since the light intensity radiation is given by the inverse-square law, $I \propto \frac{1}{R^2}$, we may abandon changes caused by corrections of R as far as $\Delta R/R \approx 0$, where R is the distance between the Sun and the considered scene. This assumption is obviously satisfied for $\Delta R \sim 10\,km$ (an approximate lighting installation diameter).
4. The measured AL level is expressed in luxes (lx) and denoted as E_{amb}.

3.2 Lighting Class Reduction

The second method of the energy saving is based on the lighting class reduction which is allowable by the standard CEN/TR 13201-1 (Standardization, 2004) For example, in hours of the reduced traffic intensity (at night, but also in weekends) a lighting class will be lower than during a traffic congestion period. If so, the performance requirements will be weaker for the former case than in the latter one.

Although this general rule seems to be similar to the lumen output scheduling discussed in the previous section, the difference is that lighting class switching is triggered by changes detected by sensors rather than by a predefined schedule. It should be remarked that any system state change detected by sensors (and leading to a lighting class update) has to persist over a given time period, e.g., 15 minutes, prior to implying a change of performance settings. Such a policy allows avoiding random alterations caused by a presence of single vehicles for example. Summarizing the above, the system behavior is adaptive and not predefined.

3.3 Lighting Profiles and Control

To unify approaches presented in subsections 3.1 and 3.2 we introduce the concept of *lighting profiles*.

A level of the ambient light, E_{amb}, being measured may be discretized and identified with one of ranges $(r_1, r_2, \ldots r_N)$, where $r_i = [t_i, t_{i+1})$ and $t_i < t_m$ for $i < m$, say $r_q \ni E_{amb}$. Note that the series $(r_1, r_2, \ldots r_N)$ covers all values of E_{amb} form zero to some maximum reachable during a sunny day, when a street lighting is switched off. In our considerations we focus only on the ranges which correspond to conditions requiring luminaires to be switched on: $\mathcal{R} = (r_1, r_2, \ldots r_k)$, where $k < N$.

Let $\mathcal{S} = \{S_1, S_2, \ldots S_m\}$ be the set of the states, corresponding to such volatile factors as the instantaneous intensity of a car traffic, persons, weather conditions and so on. Those states may be expressed either purely numerically (traffic flow is 100 vehicles per minute) or qualitatively (moderate car traffic). Granularity of a system description will depend

Table 3: Impact of the ambient light for the installation performance. *LFR* stands for *luminous flux ratio* and denotes the ratio of nominal power used, P_{eff} is the effective fixture power (i.e., incl. dimming).

E_{amb} $[lx]$	L_{avg} $\frac{cd}{m^2}$	U_o	U_l	TI $[\%]$	SR	LFR	P_{eff} $[W]$
1	0.75	0.66	0.80	8.4	0.66	0.72	59.1
5	0.76	0.80	0.87	5.4	0.79	0.43	35.3
10	0.76	0.97	0.98	0.8	0.97	0.06	4.9

on a designer's decision. Recognizing an actual system state is possible thanks to information incoming from a telemetric layer.

The general idea underlying the lighting control is switching the system adjustments according to an environment state described by a pair $(r,S) \in \mathcal{R} \times \mathcal{S}$ representing a combination of ambient light level and other environment parameters, including traffic intensity. To accomplish that we introduce the control function which may be defined in the rough approach, in the following way:

$$F : \mathcal{R} \times \mathcal{S} \to \mathcal{P},$$

where $\mathcal{P}$ is the set referred to as the set of *lighting profiles*. Each profile $p \in \mathcal{P}$ specifies unambiguously the settings (dimming levels) of relevant fixtures. In fact, F may also specify the dynamics of a change. For example, the high gradient of luminance may require more time (in seconds) to smooth transition between two states, $(r,S)_1 \to (r,S)_2$, to avoid a blinking effect.

4 CASE STUDIES

In this section we present two cases corresponding respectively to *daylight harvesting* approach (ambient light-based) and lighting class reduction.

4.1 Ambient Light Impact

We consider `BGP353 T15 DN GRN104` fixture, used in Section 2. Table 3 presents values of all relevant photometric quantities, for sample $E_{amb} \in \{1\,lx, 5\,lx, 10\,lx\}$, together with corresponding dimming levels.

The assessment of energy (cost) savings is not a straightforward task due to the variant length of the twilight duration (we focus on $E_{amb} \leq 10\,lx$). This length depends on both the geographic location of a considered scene and the time of the year. At Greenwich (51.5° N), Great Britain, it varies from 33 minutes to 48 minutes and at the equator from 20 to 25 minutes (Wikipedia, 2015).

To make at least a rough estimation of savings let us assume that the relevant twilight period for Greenwich is 40 minutes long and E_{amb} increase linearly (wrt time) within this time window. The average luminous flux ratio value during this time (1 h 20 min per day) may be computed as the arithmetic average of $LFR = 0.79$ (no ambient illuminance) and $LFR = 0$ (lamps are switched off): $LFR_{avg} = 0.79/2 = 0.395$ whence corresponding power in this period is

$$P_1 = P_0 \times LFR_{avg}.$$

In the rest of an operating time[1] $LFR = 0.79$ and the corresponding power

$$P_2 = P_0 \times LFR,$$

where P_0 is a nominal power of an installation. When comparing this with flat power supply scheme we obtain the energy saving ratio (α):

$$\alpha = \frac{P_1 \times 1.33h + P_2 \times 10.67h}{P_2 \times 12h} = 6\%.$$

4.2 Lighting Class Reduction

Figure 2 shows the averaged daily traffic intensity for subsequent quarters as measured by induction loops installed in a double carriageway road in the city of Cracow, Poland (Google Map, 2015). The avg. carriageway width on the considered section is 9.3 *m* and the avg. lamp spacing is 23.4 *m*. The computations were performed for the mounting height 8 *m* and the LED fixture `BGP353 T45 DW ECO181`. For each quarter a lighting class was determined and the corresponding *LFR* was established.

As specified by the standard the lighting class may be reduced for the considered road from ME2 through ME3b to ME4a during a day, dependently on the traffic intensity (see Fig.2). Obviously, we estimate energy savings in the night/twilight periods (3:30 pm to 7:15 am) only for the days of the traffic measurement (beginning of December).

Since the energy usage is calculated as the weighted mean:

$$E = \Sigma_{i \in \{ME2, ME3b, ME4\}} LFR_i \times P_0 \times \Delta t_i,$$

where P_0 is the installation's nominal power and Δt_i stands for an operating time for a given class, we may easily assess the power saving ratio (α) by dividing:

$$\alpha = \frac{\Sigma_{i \in \{ME2, ME3b, ME4\}} LFR_i \times \Delta t_i}{LFR_{ME2} \times [\text{Total operating time}]}$$

For the analyzed case we obtained $\alpha = 0.73$ which means that 27% savings may be reached.

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[1] The annual mean of an operating time is assumed to be 12 h.

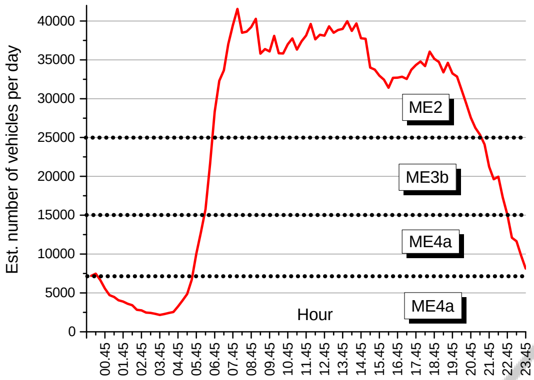

Figure 2: Average daily traffic intensity. Dotted lines separate lighting categories corresponding to intensity size.

5 CONCLUSIONS

Large annual costs of street lighting which are expected to reach over $42 billion by 2025 encourage to search for new methods of reducing the power usage. The proposed concept of lighting profiles allows for combining two such approaches based on daylight harvesting and lighting class reduction respectively. This methodology is tested in two projects: Green AGH Campus smart grid project and ISE R&D project, basing on PhoCa software which was developed at the AGH University.

Analyzed cases and obtained results show that this methods lead to significant energy and cost savings. In the presented case it was 6% energy saving by considering ambient lighting and 23% with respect of road class reduction.

In the future works we will focus on the impact of an artificial ambient light which properties are significantly different than for the natural one. In particular it is anisotropic and distance dependent.

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