UNIVERSITY POLITEHNICA OF BUCURAREST
DOCTORAL SCHOOL OF ENERGY

SUMMARY
PHD THESIS

INCREASING ENERGY EFFICIENCY IN MODERN PUBLIC LIGHTING SYSTEMS

AutHor: Ing. Ionuţ CIOBANU

PhD cOORDINATOR:Prof. Dr. Ing. George Cristian LĂZĂROIU

Bucharest 2022

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Keywords: energy efficiency, street lighting, LED energy efficiency indicators,

CHAPTER 1 INTRODUCTION

1.1 Research domain research

In recent decades air pollution has become the greatest threat to human health, from the environment and an important factor in deaths.

Energy has clean and energy efficiency are important chapters of Romania's Energy Strategy in the medium term up to 2030 and long-term to 2050.

In the contextof the need to implement energy efficiency schemes in all areas with real energy-saving potential, public lighting is becoming an important element of the energy efficiency process.

1.2. Scopul of the thesis

The purpose of this PhD thesis is to identify and present modern solutions in the field of public lighting in order to increase energy efficiency.

The implementation of an effective street lighting project largely depends on:

- analysis of local needs, existing infrastructure and available technology;
- aclear understanding of the potential electricity and cost savings to be achieved through the project.

1.3. Energy efficiency indicators for public lighting in the European Union and Romania

Indicator - is an element that gives an indication and could be any of the different statistical values that give an indication.

Related to public lighting at country level, several indicators of energy efficiencycan be identified, the most important being [1]:

- total annual electricity consumption related to the entire public lighting system in a state (l1);
- total annual electricity consumption of the entire public lighting system in relation to the final electricity consumption of a third state (l2);
- the total annual electricity consumption of the public lighting system in relation to the number of in habitants of the national energ ysystem (l3).

CHAPTER 2

INTELLIGENT SYSTEMS FOR PUBLIC LIGHTING

2.1.Components of the public lighting system

The lighting system afferent to the car traffic vehicles is made of constructions, installations and equipment with a certain specificity.

Currently, in addition to the standard components of the public lighting system presented in the internet,there are also the intelligent street lighting control elements that offer interoperability with different communication technologies and IoT (Internet of Things) platforms, while ensuring compatibility with different manufacturers of luminaires and smart city devices (light sensors , cameras, sensors for determining the quality of air, smart traffic lights).

2.2. The pillars of the public lighting system

The luminaire is the support designed to support one or more luminaires, consisting of one or more parts, according to the European standard EN 40-1:1991 on lighting flooring [2].

2.3. Power lines for supplying public lighting fixtures

The public lighting system is an electrical installation that operates at low voltage, respectively at voltages of 400 V and 230 V.

2.4.Flash points of the public lighting system and distribution boxes

The ignition points and distribution boxes are designed to carry out the distribution of electricity from the substation to the luminaire.

2.5.Lighting fixtures

The luminaire is themain element of a public lighting installation, being defined as the construction assembly consisting of the light source (classic or LED lamp), the distribution system and the space distribution of the luminous flux consisting of the reflector (lenses for LED technology) and the lens, as well as the mechanical resistance system (the housing) in which the accessories are mounted (light source,ballast, fireproof, nozzle, or LED driver).

LED luminaires also have the potential to increase the level of quality factors of the public lighting system, along with the reduction of maximum physiological blindness, improving both eye comfort and visual capacity of road users. This is why, in recent years, local public authorities in cities around the world have improved street lighting by investing in LED technologies, which can provide a unique opportunity to reduce electricity costs and maintainers, as well as increase environmental protection.

It produces the well-knownled street lighting using over 50 dedicated photometric curves depending onthetype of use.

2.6.Modern communication networks for public lighting systems

2.6.1. Lora

LoRa Alliance is a non-profit association that has become one of the largest alliances in the tech sector, committed to enabling the large-scale deployment of "Low Power Wide Area Networks (LPWAN) IoT" by developing and promoting the loRaWAN open standard® [34].

The coverage of the LoRaWAN network® globally is significant and is expanding monthly with 148 LoRaWAN network operators inn 162 countries [3].

2.6.2. ZigBee

ZigBee Alliance has developed a very low-path wireless communications standard [4].

The ZigBee architecture consists of a set of blocks called layers. Each layer performs a specific set of services for the above layer. A data entity provides a data transmission service, and a management entity provides all other services..

2.6.3. zhaga

Zhaga isestablished in 2010 as a global association of lighting companies aimed at standardizing the interfaces or components of LED luminaires, including LED modules, electronic control equipment (LED drivers) and detection sensors [5]. DiiA is the industry's global organization for the Digital Addressable Lighting Interface (DALI), the global standard for digital communication between lighting control devices.

2.6.4. KNX

KNX is an association with over 500 members, present in over 190 countries that promote the automation of buildings and public lighting. KNX devices are connected via a communication busand can be acted on through a controller. The KNX network may include lighting equipment, sensors, equipmentfor action.

2.7. Communication devices

M2M communication allows devices (modern luminaires) to connect directly to local mobile telephony via sockets (socket) devices (sockets) Nema and Zhaga. These sockets are mounted on the luminaire housing at the top andis connected with the LED luminaire driver.

2.8. Sensors for motion detection

The local public authorities that manage the public lighting systems have legislative provisions on improving the energy efficiency. Turning on lighting only where and when needed by using motion sensors, minimizes irrational use of light without compromising human safety are requirements that can be solved by using sensors tokeepmoving.

2.9.Telemanagement platform related to a public lighting system

The well-known producers of public lighting fixtures have developed a date with lighting fixtures with remote communication and telemanagement software.

Telemanagement is a complete suite of web-based software applications that provide complete remote management for the entire lighting infrastructure, both at the individual level of luminaire and group.

The telemanagement platform is designed to manage, monitor and control the lighting throughout the city, providing real-time information and analysis on the behavior of the lighting infrastructure.

The telemanagement platform offer several levels of access:

- to manage the database with the luminaires and implicitly the possibility to turn off / on or modify the operating scenarios of the luminaires. This access is generally given to companies that managethe pubic lighting system in locality
- to view and monitor the data available in the platform, but without having the possibility to order the luminaires. This access isgenerally held by representativesof the local public authoritywhoare subordinated to the public lighting service;
- to access only thepossibility of varyingthe flow of the lighting fixtures in certain areas inthe eventof an accident or crime. This access can be givento the Local Policeor, the National Policeor to the Inspectorate for Emergency Situations in the event of a car accident or offence in a certain area inorderto increase the level of illumination in the area.

Management of lighting fixtures

Each luminaire integrated in the telemanagement platform comes with the unique id and informationon the typeof luminaire, the installed power, the GPS location, the date on which it was integrated intothe platform.

The level of varying the luminous flux for public luminaires is established ona calendar basis dependingon the car traffic during the nightand taking in to account weekends or working days including the existence of performances and events get yourself at certain times of the year in different areas of the city.

Monitoring of luminaires

Luminaires shall transmit to the platform directly informationon their condition and possible mal functions in real time. This information allows the prompt initialization of a repair or replacement of the faulty luminaire.

The system can identify several defects related to the lighting, so that it can be identified exactly why a certain luminaire has failed.

Duringoperation,datacan be found at any time about the functional parameters of the luminaire: it is on/off, and other operating parameters.

Metered electricity consumption data can help optimize the response of the whole lighting infrastructure. These data can help to develop an action plan in the future and to modify the scenarios of varying the luminous flux over time intervals.

Operation and mentenanțof the luminaires

The status information ofthe luminaires is drawnin realtime at the level of the luminaire or group of lighting fixtures. Defects and down time of the luminaires are automatically recorded and notifications are sent to the platform operator. This information helps the designated staff withthe maintenance of the public lighting systemto reach the site and intervene on this equipment.

2.10. Electricity quality in public lighting

Until a few years ago, the luminaires afferent tothe public lighting system had in their composition classical light sources, the most used being of sodium vapor type. In the main course, modern LED lighting sources are mainly used.

In the electrical networkfor supplying public lighting systems, electromagnetic disturbances occur that may affect the quality of the electricity delivered to other consumers in the area.

CHAPTER 3
ENERGY EFFICIENCY

In any area that uses energy, energy efficiency is based on specific indicators.

At the level of a locality, for public lighting, several energy efficiency indicatorsare proposed, namely:

- total annual energy consumption of public lighting (kWh/year);
- the total annual energy consumption of public lighting in relation to the overall electricity consumption of the local authority(%);
- the total annual energy consumption of public lighting in relation tothe number of inhabitants of the locality (kWh/year/inhabitant);
- the total annual energy consumption of public lighting in relation to the number of luminaires (kWh/year/luminaire);
- the total annual energy consumption of public lightingin relation tothe length of the illuminated streets (kWh/km);
- the total electrical power installed of the system in relation to the number of lighting fixtures (kW/luminaire);
- the total electrical power installed of the public lighting system inrelation to the length of the illuminated streets (kW/km);
- the total installed electrical power of the public lighting system in relation to the number of inhabitants of th elocality (kW/inhabitant);
- the total luminous flux of the luminaires existing inthe locality in relation to the surface of thei lluminated streets ($lm/m^{2)}$.

The European road lighting standard EN 13201 in part 5 defines energy performance indicators. Inthis part of the European standard, the calculation of the power density indicator ($D_{P)}$ and the indicator of annual energy consumption ($D_{E)}$ is defined [6].

CHAPTER 4
STUDY ON IMPROVING ENERGY EFFICIENCY INTHE PUBLC LIGHTING SYSTEM IN BUCHAREST

4.1. The way of organization and functioning of the lighting service in București

The public lighting service is a component of the community services of public utilities defined as "the totalityof the actions and activities of public utility and of general economic and social interest carried out at the level of the administrative-territorial units under the leadership, coordination and responsibility of the local public administration authorities, in order to ensure the public lighting".

4.2.The operational management of the public lighting service in Bucharest

In 2007, the National Regulatory Authority for Communal Household Services issued the Framework Regulation for the public lighting service [7]. It applies to the stages of design, execution, maintenance of public lighting components.

In 2015, the new Regulation of the Public Lighting Service inBucharest [8]wasapproved. The lighting level is established by regulation in form with SR 13433/1999.

4.2.The evolution of the public lighting system in București in the last 20 years

With the start of the contract having as objective the delegation for the public lighting service in Bucharest, an extensive process of development and extension of the lighting on unlit days or not in accordance with the standards inforce.

According to the Energy Strategy of Bucharest Municipality carried out by Grontmij, CarlBro and ATHenerg, at the level of 2007 the electric power for public lighting was 13 MW. The annual amount of electricity used by the public lighting system for 2007 represented 57 GWh/year (1.1% of the total consumption in Bucharest) [9].

The quantitative and qualitative evolution of public lighting fixtures in Bucharest between 2010-2016 is specifiedbelow [10] :

Table. 4.1. The quantitative and qualitative evolution of public lighting fixtures in Bucharest between 2010-2016

Year of reference	**Number of luminaires**	**Technology (sodium/halogen hatred/LED)**	**Total installed** power **(MW)**	**Total** consumption **per year (GWh/year)**
2010	115.176	All	14,45	61,97
2011	116.000	All	15,12	64,88
2012	117.437	All	14,17	59,57
2013	112.015	All	14,20	59,92
2014	114.613	All	14,10	59,30
2015	115.522	All	Unidentified	59,45
2016	125.513	All	14,50 (plus 0.35 MWfestive lighting)	62,68

The tables hows that between 2010-2016 the number of luminaires (bright points) increased by about 10%, the total installed power of the rămas approximately the same. The explanation is related to the fact that, in addition to the extension of the public lighting system, there have also been measures to modernise and target consumers through the replacementof bodies with mercury, sodium or halogen with bodies using LED technology.

The evolution of the average power on the luminaire (W), the average annual electricity consumption/luminaire (kWh/year) and the cost of electricity/luminaire (lei), related to the public lighting in Bucharest between 2012-2016 is presented in the following table[11]:

Table 4.2. The evolution of electricity is also used in the related costs of the public lighting system in Bucharest between 2012-2016

Year	Medium power/ luminaire (W)	The amount of electricity used per year /lightfixture (kWh/year)	Energy cost of electric/ luminaire (lei)
2012	126,80	507,23	181,27
2013	124,20	496,80	181,27
2014	120,33	481,30	185,39
2015	122,84	491,36	181,88
2016	122,73	490,93	164,10

Between 2012-2016 the average power on the luminaire (bright point) decreasedby 3.3%, from 126,80 W/ luminaire to 122,73 W / luminaire.

CHAPTER 5
OPTIMIZATIONSIN PUBLIC LIGHTING SYSTEMS

5.1. Introduction

Optimization is the process of choosing and applying the optimal solution among several possible in certain hypotheses. In the optimization process, the problem is defined, the available variants are established, all possible variants are evaluated and the optimal variant is chosen [56].

The variables in optimizing public lighting are:

- type of lighting fixtures;
- distance between poles;
- in the high above the useful plane of the luminaire that determines the width of the poles;
- the consolation of the light point (console length);
- still the line (console and /or luminaire);
- the type of arrangement of the streets on the street,namely: unilaterally, bilaterally againsteach otherand alternating bilatera.

5.2.Case study on the results of luminical calculations in sodium and LED version

In this case study are highlighted by luminographic calculations in the program Dialux [13], performance criteria according to the lighting standard CEN/TR 13201-2003 [6], for four types of streets with lighting class ME2, ME3a, ME4a, ME5 in two situations with sodium and LED [13, 14]:

a) The "existing" situation with sodium lighting fixtures.
b) The situation "redesigned" with LED lighting fixtures placed on octagonal metal poles.

The maintenance factor used in the luminotehnci calculation is0,67 for clean space, maintenance cycle at 3 years.

5.3. Energy efficiency of the proposed 'redesigned' system compared to the 'existing' version and of the energy performance indicators specified in EN13201 in **part** 5

The energy efficiency of the "redesigned" system proposed compared to the "existing" version and of the energy performance indicators specified in EN 13201 in part 5 were calculated for traffic routes (classes ME2, ME3a, ME4a, ME5 in the en 13201-1standard).

5.3.1. Me2 class

Calculation of the energy efficiency of the proposed variant with "redesigned" system using 156W LED luminaires, compared to the "existing" version using 256 W sodium luminaire [15]:

It is found that energy efficiency has increased by around 39%, subject to compliance with the lighting performance and quality criteria, according to the LIGHTING STANDARD CEN/TR 13201-2003.

5.3.2. ME3a class

Calculation of the energy efficiency of the proposed variant with "redesigned" system using 97 W LED luminaires, compared to the "existing" version using 158 W sodium luminaire [15]:

It is found that energy efficiency has increased by around 38%, subject to compliance with the lighting performance and quality criteria, according to the LIGHTING STANDARD CEN/TR 13201-2003.

5.3.3. ME4a class

Calculation of the energy efficiency of the proposed variant with "redesigned" system using LED luminaires of 49.5 W, compared to the "existing" version using 105.4 W sodium luminaire [15]:

It is found that energy efficiency has increased by around 53%, while the performance and quality criteria of the lighting are rejected, according to the Lighting Standard CEN/TR 13201-2003.

5.3.4. ME5 class

Calculation of the energy efficiency of the proposed variant with "redesigned" system using LED luminaires of 39.5 W, compared to the "existing" version using 84.5 W sodium luminaire [15]:

It is found that energy efficiency has increased by approximately 53%, while complying with the criteria for performance and quality of lighting, according to the Lighting Standard CEN/TR 13201-2003.

CHAPTER 6
CONCLUSIONS AND PERSONAL CONTRIBUTIONS

The PhD thesis has made an analysis of modern public lighting systems, ways to increase the energy efficiency related to these systems, but also optimize countries for variable parameters of arrangement in order to decrease the electricity consumption, based on minimum investment costs.

6.1.Conclusions of the thesis

The requirements underlying the optimization in public lighting systems are related to the fulfillment of the performance criteria specified in the international lighting standard CEN/TR 13201-2003 related to each luminical class regarding: the average luminance L_{med} [cd/m^{2}], **the uniformity of the** luminance U_0 **=** L_{min}/L_{med}, the longitudinal uniformity of the luminance U**l** [%] = L_{min}/L_{max}**, maximum physiological** blindness T_i [%] and joined area ratio SR [16].

The optimization process in public lighting systems can be carried out for the following situations: partial or total modernization of public lighting and extensions of public lighting in unlit areas.

The variables identified in the process of optimizing public lighting on which therora can be acted upon are:

- the type of lighting fixturesand its electrical equipment installed;
- the distance between pillars;
- the height above the usable plane of the luminaire that determines the height of the pillar;
- the length of the console;
- inclination (console and/or luminaire);
- the type of arrangement of the stâlpilor on the street, respectively: unilateral, bilaterally face to face and alternating bilaterally.

By using the Dialux luminical calculation chart,optimization can be achieved through the section of the *arrangement optimized for luminaires.*

The optimal technical and economic final development is that which has:

- the luminaire with the electrical power installedand the **lowest;**

- **the maximum value** for the distance between the pillars (resulting in a smaller number of stâlpi on the street);

- the **minimum value** for the height of the pillars (thelower the height of the pillars will have alower price);

- the **minimum value** of the console length (the console havinga smaller length also has alower cost);

- the total investment cost for poles, consoles and luminaires in case of analysis of several types of lighting fixtures must be **the minimum** of all the analyzed variants.

Chapter II presented the intelligent systems used in modern public lighting and the benefitsofadopting them. Moderncommunication networks for public lighting systems developed by global associations of lighting companies (LoRa Alliance, Zigbee, Zhaga)have been evident. KNX) aimed at standardizing the interfaces of the components of LED luminaires, including LED modules, electronic control equipment (LED drivers) and presence detection sensors.

Chapter III aimed to identify energy efficiency indicators at the level of a locality in order to quantify the solutions for the intelligent systems adopted for the modernization of public lighting.

Chapter IV analyzed the component of the public lighting system in Bucharest, providing information about the situation of the quantitative and qualitative evolution of the elements of the street lighting system in the last 20 years, but also proposes it regarding the estimated investment costs for the transition to LED technology of the lighting fixtures.

In Chapter V, it was studied, through case studies, for the main luminical classes related to street lighting, the evolution of energy efficiency and energy performance indicators in the existing version with lighting fixtures using sodium technology at high pressure and optimized variant using LED technology.

6.2. Personal contributions of the author

In the present doctoral thesis, the following personal contributions weremade:

- carrying out bibliographic studies on the modern components of public lighting systems;
- identification through bibliographic studies of the energy efficiency indicators for public lighting at the state level;
- creating and identifying energy efficiency indicators at thelevel of a locality in order to quantify the solutions for the intelligent systems adopted for themodernization of public lighting;

- the research of the situation ofthe public lighting system in Bucharest regarding the operating regulation;
- identifying the quantitative and qualitative evolution of the elements of the public lighting system in the last 20 years inBucharest;
- establishing the estimated investment costs for the transition to LED technology of the public lighting fixtures in Bucharest;
- variable analysisor in optimizing the public lighting system for situations of partial modernization, total modernization and for its extensions;
- the development of case studies on the analysis of the evolution ofenergy efficiency and energy performance indicators in the case of an existing situationwith luminaires using sodium technology at different pressure but also of thesituationoptimized using LED technology.

6.3. Later areas of research

Energy efficiency in modern public lighting systems analyzed by this doctoral thesis is part of a very large field represented by energyefficiency.

Further research areas may include:

- thepossibility of integrating renewable energy sources into public lighting systems;
- analysis of electromagnetic disturbances produced by LED luminaires mounted inpublic lightingsystem;
- development of luminous flux varying algorithms for public luminaires over nightly time intervals depending on car traffic;
- development of public lighting systems afferent to pedestrian crossings;
- interconnection of modern public lighting systems in smart city platforms.

6.4. Dissemination of results

The dissemination of the results wasmade by the publication of a number of five scientific and scientific works in the field of the thesis. Of the published articles, three works[1÷3] are indexed in the Web of Science database, one paper [4] is in the AGIR Bulletin (Supplement Bulletin AGIR 1/2016), one paper [5] is in the Journal "Scientific Bulletin" of the Polytechnic University of Bucharest.

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